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GUIDED WAVE BASED NONDESTRUCTIVE TESTING AND EVALUATION OF EFFECTIVE ELASTIC MODULI OF LAYERED COMPOSITE MATERIALS

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Abstract. The paper presents a nondestructive technique for the evaluation of elastic moduli of layered fiber-reinforced composites. It is based on the minimization of the discrepancy between the theoretically calculated and experimentally measured dispersion curves of guided Lamb waves generated by surface-mounted piezoelectric wafer active sensors. Numerical simulation is performed in the context of 3D linear elastodynamics for anisotropic solids. It relies on the explicit integral and asymptotic representations derived for the force-generated wave fields in terms of Green's matrix of the composite structure considered. The minimization of the least-square error sum between the measured and calculated data is achieved through a real coded micro-genetic algorithm. The reliability of the proposed approach is experimentally validated via static tensile tests as well as by the frequency response evaluation.

1. Introduction

Nowadays thin-walled engineering structures made from layered composite materials become widespread in aerospace applications, automotive and shipbuilding industry, civil engineering, etc. While in service, the composites are subject to various types of negative environment impacts, mechanical shocks, damage accumulation, fatigue and aging, which lead to the degradation of their useful mechanical properties. Consequently, it is of great importance to develop reliable non-destructive evaluation (NDE) techniques capable of damage detection and identification as well as of a continuous monitoring of composite's elastic properties during the operation in a fast and non-intrusive manner [1].

One of the modern approaches, which addresses these problems, is the utilization of elastic guided waves (GW), namely, Lamb or SH-waves [2]. The waves of this type can propagate over long distances from the excitation source, interacting with any inhomogeneities and allowing for their localization and assessment through the analysis of scattered wave fields. Successful GW application in NDE systems requires reliable mathematical models and simulation tools for the evaluation of GW amplitude and dispersion characteristics. For multilayered anisotropic composites, the latter depend not only on the frequency but also on the propagation direction, resulting in complex wave patterns and complicating damage detection.

Guided waves can be also used for the evaluation of effective elastic moduli of composite materials, which are an indispensable input for computer models of ultrasonic NDE [3, 4]. The solution of such an inverse problem can be used for a noninvasive assessment of the degradation of mechanical properties during the lifetime monitoring of composite structures. Moreover, such algorithms may be employed for the investigations of the temperature and prestressed state influence on the material elastic moduli [5].

The reconstruction method, proposed below, is based on the minimization of discrepancies between the theoretically calculated and experimentally measured GW dispersion characteristics (group velocities) of the fundamental antisymmetric Lamb wave – A_0 mode. The developed algorithm is described in the second section while the results of its experimental implementation and verification are presented and discussed in the third part of the paper.

2. Algorithm for determining elastic moduli

Layered fiber-reinforced composite materials with unidirectional [0°] or cross-ply $[0^o, 90^o]_s$ lamination schemes of elementary unidirectional prepregs are considered. Within the computer models below, the specimens are assumed to consist of transversely isotropic sublayers with identical elastic properties and known density and thicknesses. The task is to determine five effective elastic moduli of the prepreg: C_{11}, C_{12}, C_{22}, C_{44}, and C_{55}. It is also assumed that the fibers of the top layer are aligned along the Ox axis, thus, the principal axes of the both types of composites coincide with the horizontal Cartesian coordinate axes (Fig. 1).

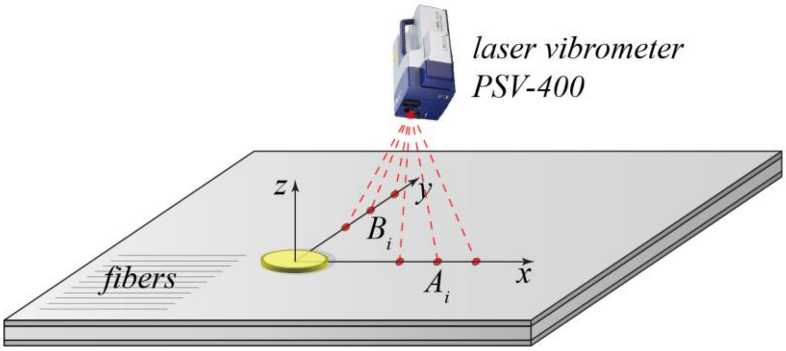

Fig. 1. Problem geometry and experimental setup sketch.

In a low frequency range, the phase and group velocities of A_0 mode propagation in the directions of principal axes depend only on the specimen's thickness, density and corresponding Young moduli (elastic constants C_{11} and C_{22}) [6]. At the same time, for mid and high frequencies, the A_0 dispersion characteristics are mainly influenced by shear elastic moduli (constants C_{44} and C_{55}). To illustrate both these statements, Fig. 2 depicts the relative deflection $\varepsilon = 100\% \cdot (v_g - v_{g,0}) / v_{g,0}$ of the group velocity calculated as a function of frequency in the course of each aforementioned elastic modulus variation. Here $v_{g,0}$ is the A_0 group velocity at frequency f [kHz] calculated for the pristine test unidirectional specimen of thickness h=1 mm with the prepreg elastic properties from Ref. [7]: C_{11}= 130.76, C_{12}= 5.26, C_{22}= 12.99, C_{44}= 3.75 and C_{55}= 5.97 [GPa]; ρ=1578 kg/m^3. The velocities v_g are acquired through the ±30% variation of the elastic modulus specified in the corresponding subplot.

The proposed algorithm consists of the following steps:

1. Guided waves are generated by the adhesively bonded piezoactuator excited with the windowed tone-bursts of varying central frequencies. Further, laser vibrometer is used for measuring out-of-plane velocities of propagating waves at the points located on the plate surface along the direction of upper sublayer fiber alignment (points A_i) and in the perpendicular one (points B_i), i=1,2,3 (Fig. 1).

2. Measured signals are processed with the continuous wavelet transform with the Gabor mother wavelet [8]. Then, the time of flight (ToF) of the wave package at each local

frequency is extracted by using the corresponding magnitude peaks of the wavelet coefficients. The A_0 group velocity is approximated as the ratio of the distances between A_i (or B_i) points to the time of traveling wave propagation between these points. The values obtained along every particular direction are then averaged.

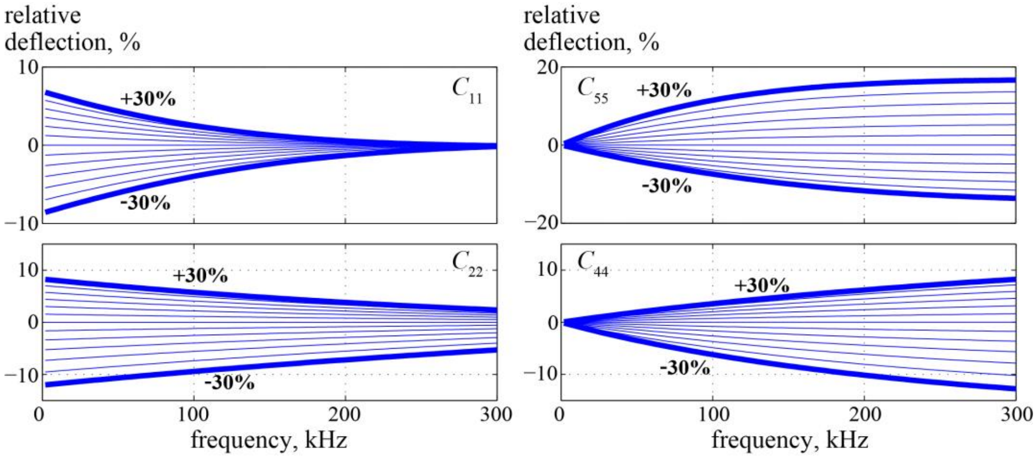

Fig. 2. Frequency sensitivity of A_0 mode group velocity to material constants variation for the unidirectional plate.

3. As soon as the experimental group velocity dispersion curves are obtained for the both directions of A_0 propagation considered, the elastic modulus reconstruction procedure is reduced to a minimization problem for the ravine objective function

$$E(\mathrm{C}) = \sum_{j=1}^{N} \left(1 - v_{g,j}^{c} / v_{g,j}^{m}\right)^2 , \tag{1}$$

where C is a candidate matrix of material constants (a varied input of the optimization problem); $v_{g,j}^{c}$ and $v_{g,j}^{m}$ are computed and measured group velocities for the propagation directions considered, N is the total amount of measured velocities. To obtain $v_{g,j}^{c}$, the algorithm of Green's matrix computation for a multilayered arbitrarily anisotropic structure [9] and asymptotic representations for group velocities of quasi-cylindrical guided waves excited in a laminate anisotropic waveguide by a localized surface load [10] are used.

4. Objective function (1) is minimized using a real coded microgenetic algorithm with a simulated binary crossover [11]. Every individual chromosome represents a candidate solution (matrix C), while its genes are specific elastic moduli.

Preliminary numerical testing of this approach on unidirectional and cross-ply laminates with known prepreg elastic properties has shown its high numerical efficiency and considerable noise stability. For example, with the input array of N=32 measured velocities (16 values of A_0 mode group velocities for each principal axis) subjected to 5 % artificial Gauss-type noise, the maximum relative discrepancy of the reconstructed elastic moduli is less than 5 % for unidirectional laminate and does not exceed 11 % for the cross-ply one.

3. Experimental verification of the algorithm

The developed approach has been experimentally tested on carbon fiber-reinforced plastic plates using the equipment facilities of Institute for Mechanics, Helmut Schmidt University, Hamburg, Germany. The measurements have been performed for composite samples with unidirectional $[0^\mathrm{o}]_4$ and cross-ply $[0^\mathrm{o}, 90^\mathrm{o}]_\mathrm{s}$ lay-ups. The specimens' dimensions are 1000×1000×1.13 mm^3, and the prepreg's density is 1482 kg/m^3; fiber volume fraction is about 52 %. Guided waves are generated by piezoelectric wafer active sensors adhesively bonded to the composite plate, while the out-of-plane surface velocities are acquired with the 1D scanning laser Doppler vibrometer Polytec PSV-400.

The results obtained for both unidirectional and cross-ply laminates after the averaging over eight genetic algorithm runs are summarized in Table 1.

Table 1. Effective elastic properties of the transversely isotropic prepreg evaluated with the proposed approach (all the values are given in GPa).

Plate type	C_{11}	C_{12}	C_{22}	C_{44}	C_{55}	E_x	E_y
Unidirectional laminate	110.5	4.23	11.8	2.59	3.71	108.6	8.05
Cross-ply laminate	106.6	3.15	8.11	2.46	3.91	104.8	6.81

To verify the obtained results, standard tensile tests have been performed on the coupons cut from the unidirectional sample. The following values of Young moduli along the principal axes have been obtained: E_x =112.4 GPa and E_y =7.69 GPa. These values are in good agreement with the restored effective elastic moduli specified in the last two columns of Table 1. A discrepancy in E_y values obtained for unidirectional and cross-ply plates are explained by a relatively low sensitivity of A_0 mode group velocity to this constant variation for a cross-ply laminate compared to the other moduli.

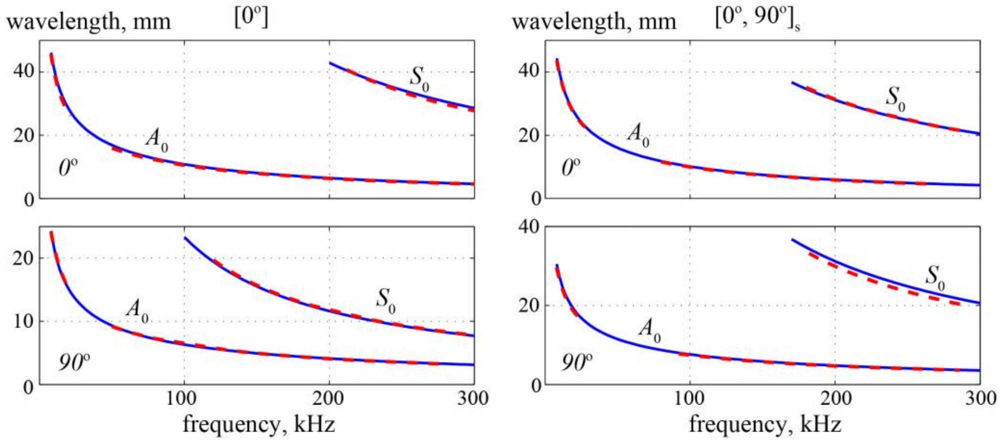

Fig. 3. Measured (dashed lines) and theoretically restored (solid lines) dispersion curves for A_0 and S_0 mode wavelengths along the fibers (top subplots) and in the perpendicular direction (bottom subplots).

As an additional test, frequency dependencies of fundamental symmetric and antisymmetric mode wavelengths calculated using the elastic constants from the first row of Table 1 have been compared with corresponding experimental values. The latter have been obtained by applying time and spatial Fourier transforms to the out-of-plane velocities scanned along the composite’s principal axes. Theoretical and experimental results are in good coincidence for both types of laminates (Fig. 3).

Moreover, the A_0 wavelengths measured at low excitation frequencies for the unidirectional composite have been utilized for an approximate estimation of Young’s moduli E_x and E_y via the relation from Ref. [6] $E_{x,y} \approx 3\rho v_p^4 / (\pi^2 H^2 f^2)$, where $v_p = \lambda f$, λ [m] is the A_0 wavelength for the corresponding direction, f [Hz] is the oscillation frequency, and H [m] is the waveguide thickness. The obtained results (E_x=97.8 ГПа and E_y=7.54 ГПа) are in good agreement with the values presented in Table 1.

4. Conclusions

A method of non-destructive evaluation of effective elastic moduli of fiber-reinforced laminate composite plates based on experimentally obtained group velocity dispersion curves of the fundamental antisymmetric Lamb mode has been developed. Its efficiency is confirmed by the conventional tensile test results as well as by the comparison of the predicted dispersion characteristics, calculated with the restored elastic moduli, with the experimental data.

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