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# Wave mode extraction from multimodal wave signals in an orthotropic composite plate

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ABSTRACT

In this paper the post-processing procedure based on the mode orthogonality is applied to extract individual waveforms at a composite plate edge from multimodal signals. To obtain the amplitudes of individual modes, numerically predicted modal through-thickness stress and displacement field values are used in the orthogonality relation. The performance of the mode extraction technique is evaluated by processing signals obtained from Finite Element (FE) modeling and experimental measurements. The propagation of the overlapping wave packets of Lamb modes $S_0$ and $A_0$ is considered along the fiber direction and perpendicular to that direction. The required experimental two-dimensional displacement components at the plate edge are measured by 3D Scanning Laser Doppler Vibrometer (3D SLDV). It is demonstrated that $S_0$ mode can be extracted very well from the signal but $A_0$ mode with slightly poorer accordance with the original waveforms and numerical predictions.



## 1. Introduction

Composite materials are widely used in highly demanding applications in several industries due to their high strength and stiffness to weight ratio and good resistance against aggressive environments. However, the reliable performance of a composite structure depends on its pre-service quality and its in-service degradation under various operating conditions. Defects can develop in the material which may lead to unwanted failures. Therefore, in order to enhance the performance and safety it is essential that critical regions in these structures are monitored during the manufacturing process and in the service.

Ultrasonic techniques have been applied successfully in the field of non-destructive testing (NDT) of composite materials [1]. Lamb modes are particularly well suited for testing large areas since they can propagate long distances, while interrogating through the thickness of the waveguide [2]. However, guided wave testing in composite materials is much more challenging than in isotropic materials. Due to the anisotropy the properties of guided waves are directionally dependent and they also suffer from the mode coupling issue [3,4]. The wave propagation in composites is often affected by the material's viscoelasticity that causes the attenuation of the waves [5,6] which limits the inspection range. Additionally, uncertainties in the determination of material elastic constants complicate the accurate use of modeling and testing techniques [7].

In this paper we focus on one major difficulty that is inherent to all kind of Lamb wave testing. This is the multimodality in measured signals [8–11]. In general, single wave mode testing is rarely achievable because the interaction of a single incident wave with a defect or structural feature can result in a complicated multimode signal due to scattering and mode conversion effects. Such a multimodal response signal is a typical result when the low frequency Lamb waves $A_0$ and $S_0$ interact with a delamination [12,13] or impact damage [14] in a composite plate. In order to simplify the interpretation of these signals it is important to separate wavepackets of different modes, as the parameters of the signal of each received mode are dependent on the geometry and location of the defects differently. Separated signals may provide more information about the defect and could be useful for the development of inverse procedures for the defect characterization [15–18].

Recently, a technique based on the Lamb mode orthogonality-relation was proposed to separate Lamb modes at the edge of an isotropic plate [19]. This is an alternative to the well-known mode extraction methods making use of the data measured on the surface of the plate [8–11,20,21] and could be the beneficial way when the plate surface is inaccessible for testing. The main advantages of the method in comparison with the classical spatial two-dimensional Fast Fourier Transform (2D-FFT) are that it is possible

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to reduce the number of monitoring points and there is no need for special mode filtering procedures [22] as obtaining amplitudes of the modes is straightforward [23,24]. Therefore it has also been a valuable tool for reducing the size of FE models for the wave propagation analysis [25,14]. Instead of using a number of surface displacements for mode extraction the orthogonality relation requires the simultaneous capturing of the through-thickness displacement and stress field of the waves in a single location of the plate. At the plate edge the orthogonality condition is simplified as the stresses equal to zero and therefore it is possible to implement the technique practically by only measuring the displacement components of the wave-field.

The approaches for efficient mode separation have been addressed in a number of studies. In previous research [20] it has been demonstrated that it is possible to separate the Lamb modes in a plate by using only two signals measured on the opposite sides of the plate at the same location. However, this technique is only capable to extract fundamental modes and needs careful calibration to achieve similar measurement conditions on both surfaces of the plate. Also, wavelet transforms have been widely used to decompose the modes from time-frequency spectrograms which can be realized only from a single point measurement [9–11,21,26]. One of the main challenges has been to separate the modes which energy spectrums overlap in the time-frequency domain. By applying dispersion compensation [10] or special signal processing techniques [26] it has been possible to separate and decouple overlapping signals with the known dispersion relations and propagation distances. Clearly, in case of the signals can be measured at the wave-guide surface these methods are more efficient compared with the current approach. However, their performance is not known when the measurement is performed at the plate edge where the scattering effects must be considered. This requires the separation not only the incident and reflected modes but also the non-propagating modes which usually arise at the plate edge and overlap with the propagating modes. This can be achieved by using orthogonality relation which is insensitive to the time-frequency overlap of the modes and there is no need to determine the propagation distance of the arrived wave modes as the separation is performed exclusively in the frequency-domain.

The aim of this paper was to apply the Lamb mode orthogonality based method to extract overlapping guided modes propagating along the in-plane symmetry axes of an orthotropic plate. The paper starts with the demonstration of the technique in FE models, and is followed by the experimental validation using a 3D SLDV. Both FE and experimental results show that the method is capable to separate signals of propagating and non-propagating guided modes in the time domain in an anisotropic plate.

## 2. FE modeling and orthogonality-based post-processing of the results

Wave propagation was simulated by using the finite element modeling software Ansys [27]. Fig. 1 shows the two-dimensional FE model for Lamb waves propagating towards the edge of the plate along the $x$-direction which represents the direction along the fibers, and $(x, y)$ is the plane of symmetry. Four-node plain strain elements were chosen for the meshing, with no damping

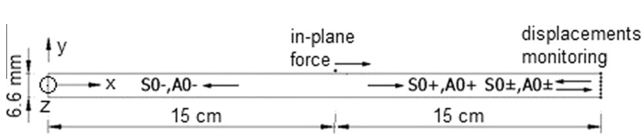


**Fig. 1.** Plane-strain FE model of $A_0$ and $S_0$ interacting with an edge of a plate.

or attenuation effects. 10 elements along the thickness and 300 elements along the length of the plate were used, which are sufficient for the convergence of the wave solutions. The material properties, as listed in Table 1, have been experimentally obtained for the same glass-fiber/vinylester composite material. The measurements were based on Lamb wave and natural vibration measurements and gave three elastic and shear moduli [28]. The Poisson's ratios are estimated. In case of modeling wave propagation in the direction perpendicular to the fibers the indexes $x$ and $z$ of elastic constants were interchanged.

The waves were excited in the middle of the plate length by applying the in-plane load on the plate surface. This ensures that both Lamb modes antisymmetric $A_0$ and symmetric $S_0$ are generated with comparable amplitudes. The excitation was a 10-cycle sinusoid at 100 kHz windowed by a extended cosine bell function. The signals were simulated long enough to see repetitive reflections of the modes from the plate edges and also the overlap of the wave packets of the modes due to the different propagation velocity of $A_0$ and $S_0$ modes.

The total field at the plate edge is composed of several eigenmodes of the plate. The displacement vector $\mathbf{U}_{tot}$ and stress tensor $\sigma_{tot}$ can be expressed as

$$\begin{pmatrix} U_x \\ U_y \end{pmatrix}_{tot} = \sum_{n=1}^{\infty} r_n \begin{pmatrix} u_x \\ u_y \end{pmatrix}_n \text{ and } \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix}_{tot} = \sum_{n=1}^{\infty} r_n \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix}_n, \quad (1)$$

where $r_n$ is the complex amplitude of each mode $n$ in the total field. For the extraction of the individual guided modes (incident or reflected) from the total field at the plate edge predicted by the FE model, the general orthogonality relation [23] was used. The complex amplitude $r_n$ of any mode $n$ can be obtained in the frequency domain as [19]

$$r_n = \frac{\int_0^h [(\sigma_{xy})_n U_y - (\sigma_{xx})_n U_x] dy}{2\int_0^h [(\sigma_{xy})_n (u_y)_n - (\sigma_{xx})_n (u_x)_n] dy}, \quad (2)$$

where $h$ is the thickness of the plate. Here it is important to note that the total wave field at the edge does not contain only propagating modes with real wave-numbers but also non-propagating modes with complex wave-numbers to satisfy the boundary conditions of the wave-field at the plate edge [29,30]. However, they belong to the same Lamb wave family and must satisfy the orthogonality condition which creates the possibility to separate them. Incident and reflected wave modes can also be distinguished by their orthogonal relations in their modal quantities.

To post-process time-domain signals of the total wavefield, all 11 points along the plate edge in the $y$-direction were monitored and the recorded data were transformed into the frequency-domain by using FFT. At each frequency step the through-thickness displacement and stresses of the desired extracted mode component $n$ were calculated and modal amplitude $r_n$ was pre-

**Table 1**
Material properties of an orthotropic plate used for numerical modeling.

| Elastic constants | Value |
|---|---|
| $E_x$ | 40.0 GPa |
| $E_y$ | 15.4 GPa |
| $E_z$ | 15.3 GPa |
| $\nu_{xy}$ | 0.3 |
| $\nu_{xz}$ | 0.3 |
| $\nu_{yz}$ | 0.5 |
| $G_{xy}$ | 6.0 GPa |
| $G_{xz}$ | 5.5 GPa |
| $G_{yz}$ | 4.8 GPa |
| $\rho$ | 1940 kg/m$^3$ |