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LAMB WAVE SCATTERING ANALYSIS FOR LAMINAR COMPOSITES

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Abstract. *This paper investigates the scattering of Lamb waves in layered composite structures and presents an approach to analyzing their dynamic behavior using wavelet transform techniques. The focus is placed on the decomposition of the energy spectrum of scattered signals in order to extract detailed dispersion characteristics. The methodology is based on the application of continuous wavelet transforms, which enable time-frequency localization of wave components and allow for the reconstruction of phase velocity dispersion curves with high resolution in narrow frequency bands. A key feature of the proposed approach lies in the selective reconstruction of dispersion curves based on the frequency content of the wavefield, which significantly enhances the interpretability of scattered signals. It is shown that the narrowband nature of the dispersion curve reconstruction plays a critical role in accurately capturing the evolution of guided wave modes, particularly in the presence of defects or structural discontinuities. The study demonstrates that an essential condition for increasing the sensitivity of signal processing methods to subtle frequency components is the suppression of high-amplitude components, which tend to mask the presence of weak but diagnostically significant spectral features. To address this issue, a filtering procedure is introduced, allowing the elimination of dominant harmonics and improving the visibility of localized scattering effects. This filtering step enhances the contrast in the time-frequency domain and enables more effective detection of phase shifts and mode conversions caused by internal anomalies. The developed wavelet-based framework provides new insights into the interaction mechanisms of Lamb waves with layered inhomogeneities and opens up opportunities for improved defect characterization in composite materials. The results are relevant for non-destructive evaluation and structural health monitoring applications where precise identification of guided wave features is essential.*

Key words: *Lamb wave, layered composites, dispersion curve reconstruction, signal filtering, non-destructive evaluation, scattering analysis.*

Introduction.

Lamb wave scattering in laminar composites has emerged as a central topic in the physics of wave propagation, nondestructive testing, and structural health monitoring. These guided elastic waves, propagating in thin plates, possess distinct dispersion characteristics, supporting multiple symmetric (S) and antisymmetric (A) modes whose behavior is strongly influenced by frequency-thickness products, material anisotropy, and boundary conditions [1]. In laminated composites, composed of multiple bonded plies with direction-dependent mechanical properties, wave propagation phenomena are significantly more complex than in isotropic homogeneous media [2]. The study of scattering mechanisms within such materials is essential for understanding how internal features such as delaminations, voids, cracks, ply terminations, or material inhomogeneities affect the transmission and conversion of Lamb waves. Scattering involves redistribution of wave energy across multiple modes and directions, often accompanied by changes in amplitude, phase, and group characteristics. When Lamb waves encounter structural discontinuities, the interaction results in partial reflection, mode conversion, and forward scattering into multiple propagating and non-propagating components [3, 4]. These phenomena differ markedly depending on whether the incident wave is of symmetric or antisymmetric type. Symmetric modes, typically associated with in-plane displacements, tend to exhibit higher phase velocities and lower sensitivity to surface perturbations, whereas antisymmetric modes, which are predominantly out-of-plane, are more responsive to defects such as delaminations or interfacial debonding due to their stronger interaction with geometric asymmetries. The scattering behavior of each mode must be carefully analyzed with respect to its modal content, directionality, and the intrinsic anisotropy of the laminate, especially since composites exhibit coupling between in-plane and out-of-plane dynamics [5, 6]. The distinction between phase and group velocities is critical in interpreting Lamb wave behavior. Phase velocity determines the rate at which the wavefronts propagate and is dependent on the dispersion characteristics of the medium, while group velocity reflects the speed at which energy or information is transmitted. These velocities are generally non-identical in dispersive media such as composites, and their separation becomes crucial when attempting to isolate specific scattering events or interpret time-domain measurements. Structural decomposition of Lamb wave fields has proven to be a powerful technique for isolating modal contributions and separating scattered signals from incident ones. In such decomposition, the total measured field is expressed as a superposition of incident and scattered wave components, each characterized by distinct modal signatures [7, 8]. This process enables the identification of energy redistribution among modes and facilitates inverse scattering approaches to reconstruct defect geometry or material parameters. Structural decomposition also supports time-reversal techniques and optimal sensor placement strategies in complex geometries. Among the tools for signal interpretation, the zero-crossing technique has shown particular promise due to its robustness and simplicity in estimating phase shifts, arrival times, and modal transitions in the presence of noise. This method tracks the zero crossings of received signals to determine subtle time delays and identify mode conversions resulting from scattering interactions. Unlike amplitude-based methods, which are sensitive to attenuation and signal distortion, zero-crossing techniques provide reliable estimates of travel time differences, allowing for enhanced resolution in detecting and localizing small-scale anomalies. They are especially useful when applied in conjunction with group velocity analysis and are compatible with real-time monitoring systems employing embedded piezoelectric transducers. Scattering analysis in laminated composites further benefits from advanced numerical modeling, often based on semi-analytical finite element methods, spectral element approaches, or high-order polynomial collocation schemes, which accommodate the layered geometry, interface conditions, and anisotropic elasticity of the materials. Such models, validated against experimental data, allow detailed mapping of scattering patterns, interaction coefficients, and modal energy transfer, forming the basis for forward and inverse simulations. Experimentally, techniques such as scanning laser Doppler vibrometry, air-coupled ultrasonics, and phased-array piezoelectric systems are employed to capture scattered wave fields with high spatial and temporal resolution [9, 10]. These measurements support calibration of computational models and enable full-field visualization of scattering effects. Time-frequency analysis, especially using continuous wavelet transforms, has proven invaluable for resolving overlapping modes and identifying mode conversions in broadband signals. In practical applications, Lamb wave scattering analysis is vital for detecting early-stage damage in aerospace structures, wind turbine blades, and high-performance automotive components. The sensitivity of different modes to specific defect types provides a basis for tailored inspection protocols, where excitation frequency, mode type, and sensor configuration are optimized to maximize detection capabilities. Symmetric modes may be favored for detecting through-thickness cracks or fiber breakage, while antisymmetric modes are more effective for revealing surface defects or delaminations. Moreover, by analyzing the differential scattering behavior across multiple directions and frequencies, anisotropy-induced asymmetries can be exploited to infer fiber orientations or identify ply-level variations. In the context of health monitoring, continuous Lamb wave interrogation, combined with real-time signal processing based on structural decomposition and zero-crossing detection, offers a pathway toward autonomous assessment systems. These systems aim to provide instantaneous feedback on structural integrity, integrating multi-modal scattering data to detect, classify, and localize damage under varying operational and environmental conditions. As composite structures evolve toward smart architectures with embedded sensors and actuators, the role of scattering analysis becomes increasingly central to ensuring safety, performance, and durability. The theoretical understanding of Lamb wave scattering, coupled with algorithmic advances in signal interpretation and experimental techniques for full-field visualization, continues to push the boundaries of what is possible in nondestructive evaluation of laminated materials. Ongoing research is focused on extending current models to account for nonlinearities, temperature effects, and manufacturing imperfections, while simultaneously reducing computational cost to enable high-speed implementation in field settings. Ultimately, Lamb wave scattering in laminated composites stands at the intersection of applied mechanics, wave physics, and material science, representing not only a rich field of academic inquiry but also a cornerstone of next-generation structural diagnostics and intelligent design.

Materials and results

According to the zero-crossing technique, at least two signals are required, recorded by two receivers located at two different and relatively close positions x_i and x_{i+1}. The Lamb wave source is characterized by constant coordinates and is excited by a broadband packet $s(t)$. In general, these signals contain information about the phase velocity $c_p(f)$, which must be extracted by signal processing.

The velocity of the wave packet on the surface of the plate affects the Lamb wave signal $u_i(t)$ at a distance x_i

$$u_i(t) = FT^{-1}\left[S(f)\cdot H(f)\right]. \tag{1}$$

where

FT^{-1} is the inverse Fourier transform;

$S(f)$ is the Fourier transform of the incident pulse $s(t)$.

The transfer function for Lamb waves propagation has the form

$$H(f) = \exp\left[-j\frac{2\pi f x_i}{c_p(f)}\right]. \qquad (2)$$

The zero crossing method is based on the delay times t_{im} and $t_{(i+1)m}$ of the propagating waves. The delay times are calculated from the characteristics of the signals recorded at different positions x_i and x_{i+1}. These signals are analyzed according to the zero crossing algorithm for relative amplitude A′ (see Fig. 1).

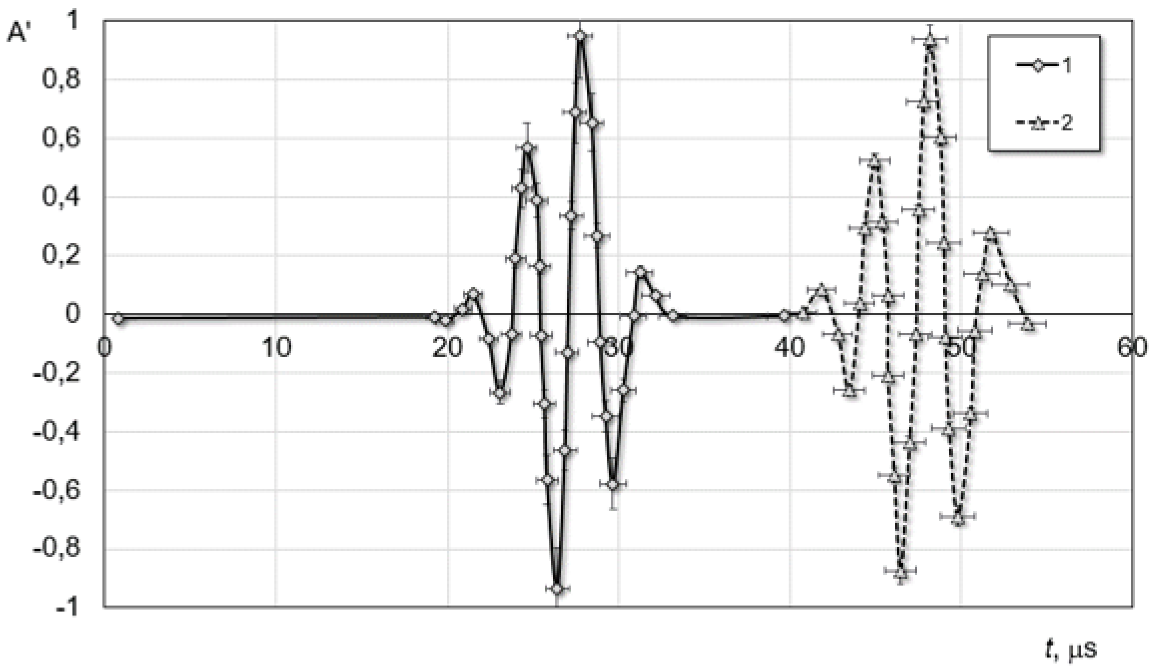

Figure 1 - Wave form of received signals:

1 – $u_i(t)$, **2 –** $u_{i+1}(t)$

The number of measured zero crossing moments is $m = 1, 2, \ldots, M$, where M is the total number of analyzed zero crossing moments. In the second stage of the zero crossing technique, the phase velocity c_{pm} of the propagating wave at a given distance can be estimated using the following formula

$$c_{pm} = \frac{\Delta x_i}{\Delta t_{im}} = \frac{x_{i+1} - x_i}{t_{(i+1)m} - t_{im}}. \qquad (3)$$

where

Δx_i is the distance between two neighboring positions;

Δt_{im} is the signals delay time difference.

The time delay Δt_{im} can be calculated based on the data on the delay times of the zero-crossing t_{im} and $t_{(i+1)m}$. The frequencies f_m, to which the calculated phase velocities c_{pm} correspond, are calculated for the duration of half the period between two adjacent zero-crossing points m and $m + 1$

$$f_m = \frac{1}{2[t_{i(m+1)} - t_{im}]}. \tag{4}$$

Each segment of the dispersion curve is uniquely defined by a set of phase velocity and frequency pairs D (f_m, c_{pm}). Analysis of the calculated propagation characteristics of Lamb wave packets showed that the proposed measurement method has one main limitation. The phase velocity dispersion curves are reconstructed only in a relatively limited bandwidth around the central frequency of the signal. Consequently, information on a part of the frequency spectra of the signal was lost. To solve this limitation and reconstruct the phase velocity dispersion curves of guided waves in the widest possible frequency ranges, it was proposed to use the spectral decomposition method.

According to Fourier theory, any signal s (t) can be expanded into trigonometric functions as follows

$$S(j\omega) = \int_{-\infty}^{\infty} s(t)\exp(-j\omega t)dt = S(\omega)\exp[-j\varphi(\omega)]. \tag{5}$$

where

ω is the angular frequency;

$j = \sqrt{-1}$;

$S(\omega)$ is the amplitude frequency response;

φ (ω) is the phase frequency response.

It can be stated that the frequency response of the signal corresponding to the Lamb wave packets is the result of such a decomposition. The modulus of the complex spectrum represents the amplitudes of the various frequency components. The signal spectrum corresponds to the interval in which the dominant frequency components are concentrated in the frequency band around the maximum of the spectrum. These features are the reason that without filtering the phase velocity dispersion curve will be reconstructed in a narrow frequency band around the central frequency. Therefore, a necessary condition for increasing the sensitivity of the signal processing method to frequency components with small amplitudes is the procedure of filtering the frequency components that correspond to higher amplitudes (see Fig. 2).

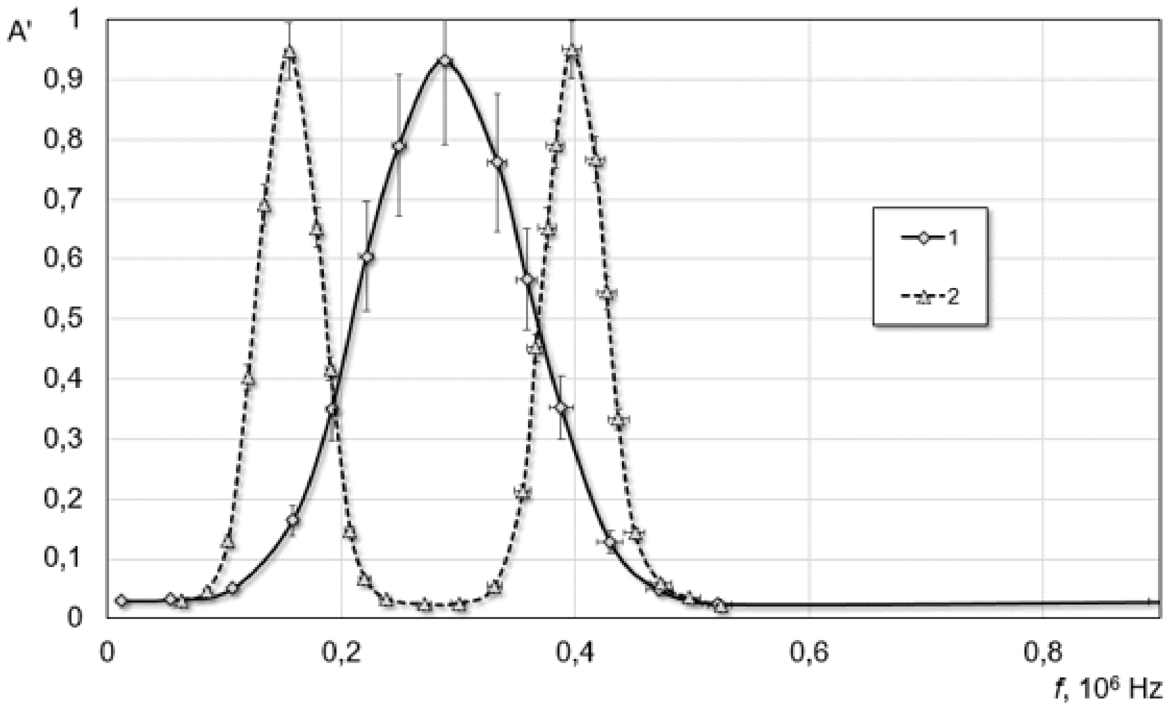

Figure 2 - Frequency spectrum of Lamb wave signal:

1 – signal**; 2** – filter

The zero-crossing algorithm assumes the possibility of decomposing the measured signals u_i(t) at different distances into a set of signals with a limited bandwidth u_{ik}(t). Such a procedure becomes possible provided that the signals u_i(t) are filtered using bandpass filters with a narrower bandwidth than the bandwidth of the incident spectrum.

At the next step for each filtered signal uik(t) the delay times t_{imk} and $t_{(i+1)mk}$ are estimated. In this way, the phase velocities c_{pmk} and frequencies f_{mk} are calculated. Then, the obtained sets (f_{mk}.c_{pmk}) can be represented as segments of the phase velocity dispersion curve.

Each section of the dispersion curve obtained using one of the filters can be reconstructed in a relatively narrow passband. In addition, scanning the filter's central frequency in wide frequency ranges will allow covering a large part of the falling spectrum.

Summary and conclusions.

The spectrum decomposition technique uses frequency components around the spectrum maximum as working objects. The disadvantages of the method include the narrow-band nature of the phase velocity dispersion curve reconstruction. It should be noted that scanning the filter center frequency in wide frequency ranges will cover most of the incident spectrum. Analysis of the calculation results indicates the possibility of effective segmentation of the spectral curve.

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