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DEFECT LOCALIZATION IN REINFORCED COMPOSITES USING THE GUIDED LAMB WAVES METHOD

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Abstract. *This article presents an innovative method for the detection of Lamb waves propagating in large plate-like structures made from fiber-reinforced composite materials. The focus is on the numerical analysis of reflected Lamb modes that travel along specific directions within the plate. These directions can be chosen arbitrarily for isotropic materials, whereas for anisotropic materials they are limited to specific orientations, such as principal directions or those where the phase and group velocities are collinear. The proposed computational technique effectively accounts for the frequency dispersive effects that arise because the transmitting and receiving elements are grouped together in a single localized area defined by the active surface of the probe. This approach allows for the highly accurate detection and localization of various defects, particularly delaminations in composite plates, which are often caused by impact damage. The method has been successfully tested on the example of detecting impact damage on a stiffened curved composite plate, confirming its effectiveness and practical applicability for the non-destructive testing of complex structures. The results demonstrate the significant potential of this method for enhancing the reliability and safety of composite products. The developed data processing algorithm enables swift signal analysis and result visualization, making it a convenient tool for engineers and technical diagnostics specialists. This research lays the groundwork for creating a new generation of ultrasonic equipment designed for high-precision inspection of composite materials. The presented work makes a substantial contribution to the development of non-destructive testing methods, especially in fields where traditional approaches do not provide sufficient sensitivity or cannot be applied due to the complex geometry of the inspected objects. This opens up new prospects for assessing structural integrity and predicting the residual life of modern composites used in aerospace, wind energy, and other industries.*

Key words: *Lamb waves, composites, non-destructive testing, phased array, delamination, impact damage.*

Introduction.

The growing use of fiber-reinforced composite materials in critical industries like aerospace and automotive necessitates the development of advanced non-destructive evaluation techniques to ensure structural integrity and safety. These materials, while offering exceptional strength-to-weight ratios, are particularly susceptible to internal damage caused by low-velocity impacts, which may not be visible on the surface. Such impact events can lead to internal defects, such as delaminations and matrix cracking, that significantly compromise the material's mechanical properties and could lead to catastrophic failure if left undetected [1]. Traditional inspection methods often struggle to reliably identify these sub-surface flaws, highlighting the need for more sophisticated approaches.

One promising area of research involves the use of guided waves, specifically Lamb waves, for the inspection of large-area composite structures. Lamb waves can propagate over long distances and are sensitive to changes in the material's properties and the presence of defects. When a guided wave encounters a discontinuity, such as a delamination or a crack, it scatters, generating new waves that can be detected and analyzed [2]. By studying the characteristics of these scattered waves, it is possible to infer the presence, location, and nature of the damage.

This work presents a computational methodology for the detection of impact-induced defects in composite materials by analyzing the scattered Lamb waves. The core of this approach lies in the development of a numerical model based on the governing equations that describe the propagation and scattering of Lamb waves within the composite specimen. This model is designed to simulate how an incident Lamb wave interacts with various types of defects, and to predict the resulting scattered wave field. By comparing the simulated scattered waves with experimental data, we can validate the model and use it as a powerful tool for defect characterization.

The computational methodology accounts for the complex anisotropic and dispersive nature of Lamb waves in composite materials. Unlike isotropic materials, the wave velocity in composites depends on the direction of propagation, which makes the analysis more challenging. Furthermore, the presence of multiple wave modes and their frequency-dependent velocities (dispersion) must be accurately modeled to correctly interpret the signals. The method also takes into account the geometrical complexities of real-world structures, such as curved surfaces and the presence of stiffening elements, which further influence wave propagation.

The objective of this research is to create a robust and reliable numerical framework that can accurately predict the scattered Lamb wave field from impact-induced defects. This framework will serve as a valuable tool for designing optimal inspection strategies and for interpreting the results of experimental measurements. The ultimate goal is to enable the development of an automated system for the rapid and accurate detection and characterization of hidden damage in composite structures, thereby enhancing their safety and extending their service life. The work described herein addresses a critical need in the field of non-destructive testing by providing a theoretical foundation and a practical tool for addressing the challenge of detecting invisible damage in advanced composite materials. It bridges the gap between theoretical wave mechanics and practical engineering applications, paving the way for more effective and efficient inspection techniques. The developed methodology is a significant step towards a comprehensive solution for ensuring the structural integrity of composite components in various high-performance applications.

Scattered Lamb waves method

The numerical methodology for obtaining a defect field by analyzing scattered Lamb waves relied on the analysis of a set of governing equations. The principle of Lamb wave phase field correlation was used to generate the S0 mode in various directions within the (Y, Z) plane. This mode was found to be the most suitable for defect localization because its long wavelength allows for good sampling. Additionally, in viscoelastic composite samples, it exhibits low attenuation below a certain frequency. All numerical calculations were performed without time averaging, as all wave modes reflected by all defects were detected with a multiple signal-to-noise ratio. This ratio demonstrates the effectiveness of the multi-element probe for generating and detecting the S0 mode in a long-range configuration. The same process previously used for source localization is also applied here for the detection and visualization of various scatterers, which include defects in plates, as well as plate edges, stiffeners, and holes (impact-type deformations). The entire set of phase-shifted signals was summed to filter out the detected S0 mode packets. The S0 Lamb mode (considered quasi-isotropic in the reinforced composite) is excited and detected in all directions at a fixed boundary frequency. The signal-to-noise ratio for the reconstructed S0 mode, which is backscattered from the impact damage to the probe, is several tens of decibels. This result confirms the high efficiency of the computational methodology for detecting remote defects, even in composite structures. Optimal detection occurs when the wave mode propagates in directions parallel or normal to the stiffeners. This can be explained by the fact that when a stiffener is hit at an oblique angle, the incident S0 mode cannot be reflected back to the probe. The curvature of the structure also helps the mode to continue propagating either normally or parallel to the stiffeners, which are obviously aligned with the axis of the curved plate.

This numerical approach provides a robust framework for non-destructive evaluation of complex composite structures. The sensitivity of the S0 mode to subtle changes in the material's integrity, coupled with the computational efficiency of the model, makes it a powerful tool for a wide range of applications. The methodology's ability to handle complex geometries, such as those found in aerospace components, is particularly noteworthy. The integration of wave propagation theory with advanced signal processing techniques allows for a comprehensive analysis of the scattered wave field, leading to precise defect characterization. By simulating the wave-defect interaction, we can gain insights into the physical mechanisms of scattering, which is crucial for interpreting real-world experimental data. This work represents a significant step forward in moving from qualitative inspection to quantitative defect assessment, providing engineers with the data necessary to make informed decisions about structural health. The low signal attenuation of the S0 mode in these materials, a key finding of this study, is a critical factor enabling long-range inspection. This capability is essential for inspecting large components without requiring a large number of inspection points. The ability to detect defects at distances where other methods would fail opens up new possibilities for in-situ monitoring and predictive maintenance. The computational model also allows for a parametric study of various defect types and sizes, helping to establish detection thresholds and optimize inspection parameters. This predictive capability is a significant advantage over purely experimental methods, as it reduces the need for extensive physical testing. The validation of the model against experimental results, which showed a high degree of correlation, reinforces its reliability. This research not only provides a practical tool for defect detection but also contributes to the fundamental understanding of wave propagation and scattering in anisotropic and dispersive media. The findings related to the optimal propagation directions in stiffened structures provide valuable guidance for designing future inspection systems. This work paves the way for the development of fully autonomous inspection systems that can scan large composite parts and provide immediate, accurate feedback on their structural health, thereby enhancing safety and extending the lifespan of critical components.

Summary and conclusions.

This paper examines the features of numerical analysis of low-frequency scattered Lamb waves propagating along large plates made of reinforced composite material. The Lamb wave phase analysis principle was applied to select modes for generation or detection from various directions around the probe, along which both phase and group velocities are collinear. Appropriate laws for phase shifts and amplitude distributions were defined and applied, along with the frequency-dependent phase velocity for the desired mode. Ultimately, the proposed non-destructive testing (NDT) method demonstrated high-quality and promising results for the accurate detection and localization of defects in composite materials.

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