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Research Progress and Future Trends in Ultrasonic Characterization of Fiber–Matrix Interfaces

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Abstract

As the most critical yet weakest structural unit within composite materials, the fiber–matrix interface plays a decisive role in determining the overall strength and service life of the material. Ultrasonic characterization techniques, owing to their high sensitivity, quantitative capability, and potential for online monitoring, have become a vital approach for investigating interfacial damage and bonding performance. This paper provides a systematic review of the development of ultrasonic characterization methods for fiber–matrix interface evaluation over the past five decades, with particular emphasis on the major advancements since the 2010s in laser ultrasonics, guided wave inspection, multimodal data fusion, data-driven analysis, and inversion algorithm optimization. Furthermore, the representative applications and engineering trends of these methods in wind energy, aerospace, automotive, and civil engineering are discussed. Finally, in light of the recent rise of artificial intelligence, digital twins, and multiphysics modeling, the paper envisions future directions for ultrasonic interface characterization toward greater intelligence, real-time capability, and standardization.

Keywords

Fiber–matrix interface, ultrasonic characterization, laser ultrasonics and guided waves, data-driven inversion and multimodal fusion, structural health monitoring.

1. Introduction

Composite materials, renowned for their high specific strength, high specific stiffness, and excellent fatigue resistance, have been widely applied in aerospace, wind energy, transportation, and civil engineering. However, the overall performance of composites is determined not only by the intrinsic properties of the fibers and matrix but, more critically, by the characteristics of their interfacial region. Serving as the core zone for stress transfer and energy dissipation, the fiber–matrix interface exerts a direct influence on the bonding strength, damage evolution, and degradation mechanisms of the composite, thereby determining its service life and structural integrity. Consequently, accurately characterizing the interfacial mechanical behavior and microscale damage state has long been one of the central scientific challenges in the field of composite materials research.

Among various nondestructive testing methods, ultrasonic inspection has emerged as a key approach for investigating fiber–matrix interfaces, owing to its high sensitivity, strong penetration capability, and potential for quantitative analysis. Since the advent of the scanning acoustic microscope in the 1970s, ultrasonic techniques have enabled the visualization of interfacial defects, marking a transition from qualitative observation to quantitative measurement in interface characterization. In the 1990s, with the introduction of interfacial spring models and stiffness parameter inversion methods, researchers were able to infer interfacial bonding properties from ultrasonic reflection or transmission signals, thereby achieving quantitative evaluation of interfacial mechanical characteristics. Since the beginning

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of the 21st century, rapid advancements in signal processing, finite element simulation, and inversion algorithms have significantly improved the resolution, accuracy, and computational efficiency of ultrasonic characterization, extending its application scope from single interfaces to multilayer composite structures.

Particularly since the 2010s, ultrasonic characterization of interfaces has entered a new phase of rapid evolution. Research focus has progressively shifted from conventional contact-based testing and linear inversion toward emerging approaches such as laser ultrasonics, guided wave inspection, multimodal data fusion, and data-driven analysis. Laser ultrasonics enables non-contact excitation and detection, significantly enhancing adaptability for complex surface inspections. Guided wave techniques can cover large-scale regions, demonstrating high efficiency in detecting interfacial damage within laminated and adhesively bonded structures. Meanwhile, the integration of multimodal fusion and machine learning has transformed interface characterization from single-dimensional physical measurements to multi-source information fusion and intelligent identification. These advancements have greatly expanded the application boundaries of ultrasonic techniques in the study of composite material interfaces.

Meanwhile, advancements in inversion algorithms and computational resources have further propelled the development of this field. Nonlinear inversion methods based on optimization algorithms-such as genetic algorithms, Bayesian inference, and conjugate gradient methods-have enabled the stable extraction of interfacial stiffness, damage parameters, and other physical quantities even under high-noise conditions. The introduction of GPU-based parallel computing and real-time data processing has reduced the computational time of ultrasonic inversion from several hours to minutes or even seconds, making online monitoring and process control during manufacturing increasingly feasible. In addition, the recent emergence of techniques such as nonlinear ultrasonics, phase-sensitive detection, and high-frequency acoustic microscopy has made it possible to sensitively identify early-stage damage and weak interfaces, providing critical support for the service life prediction and structural health monitoring of composite materials.

With continued research advancements, ultrasonic characterization of fiber–matrix interfaces is gradually transitioning from laboratory studies to engineering applications. In representative fields such as wind turbine blades, aerospace composite structures, lightweight automotive components, and civil infrastructure, ultrasonic testing has been employed to evaluate interfacial debonding, interlayer delamination, and fatigue degradation, with online monitoring and automated inspection already realized in certain scenarios. However, large-scale implementation still faces numerous challenges, including significant multipath effects, complex mode coupling, strong environmental interference, and limited algorithm generalization. Balancing detection sensitivity with enhanced robustness, interpretability, and adaptability to field conditions has thus become a central challenge in current research.

Building upon the above background, this paper provides a systematic review of the developmental trajectory and methodological evolution of ultrasonic characterization techniques for fiber–matrix interfaces. It focuses on recent advances and engineering trends in areas such as laser ultrasonics, guided wave inspection, multimodal data fusion, data-driven inversion, and weak interface detection. Further discussions address key issues related to inversion algorithm optimization, computational acceleration, and field implementation. On this basis, the paper outlines future research directions in cross-scale modeling, physics–data fusion, digital twin integration, and standardization. The aim of this work is to offer a comprehensive overview and conceptual framework to guide both theoretical research and engineering applications of ultrasonic interface characterization.

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2. Integration of Laser Ultrasonics and Guided Waves

Laser ultrasonic technology matured rapidly during the 2010s, with its core advantage lying in non-contact excitation and detection. By generating thermoelastic waves or plasma-induced shocks on the material surface through laser pulses, researchers can excite ultrasonic signals without the need for coupling agents[2]. This characteristic is particularly advantageous for complex or hard-to-access composite components, such as aircraft engine blades, composite skins, and wind turbine blades. Compared with traditional contact transducers, laser ultrasonics eliminates the influence of coupling instability on data quality, thereby significantly improving the consistency and reliability of inspections.

Meanwhile, guided wave techniques (such as Lamb and Rayleigh waves) have gradually become essential tools for large-area detection of interfacial damage. Guided waves can propagate over long distances within laminated plates and are highly sensitive to interlayer debonding and interfacial degradation [3]. In practical applications, researchers often utilize the group velocity, attenuation rate, and dispersion characteristics of guided waves to identify damage. For example, Su et al. [1] employed Lamb waves for large-scale monitoring of aerospace composite panels and enhanced sensitivity to specific interfacial depths through mode selection.

When laser ultrasonics is integrated with guided wave techniques, their respective advantages are further amplified. Laser excitation enables non-contact generation and scanning, while guided waves provide large-area coverage for rapid screening. Recent studies have reported integrated laser-excitation–guided-wave-reception systems applied to wind turbine blades and large composite structures, achieving preliminary inspection of several square meters within minutes [4]. However, this approach also has limitations: excessive laser energy may induce thermal damage, and mode coupling or boundary reflections can complicate signal interpretation. To address these challenges, researchers commonly incorporate advanced signal processing techniques-such as time–frequency analysis and wavelet transforms-to enhance the reliability and interpretability of the results.

3. Multimodal Fusion and Data-Driven Approaches

To overcome the limitations of single ultrasonic methods, a research trend toward multimodal fusion emerged in the late 2010s. By integrating different physical inspection modalities-such as ultrasound combined with X-ray computed tomography (CT), infrared thermography, or eddy current testing-researchers can characterize interfacial states from mechanical, geometric, and thermal perspectives. For instance, Katunin et al. [5] reported a method that fuses ultrasonic inspection results with X-ray CT imaging for evaluating impact damage in composite structures. The study demonstrated that ultrasonic testing excels at detecting interfacial defects such as delamination and debonding, while X-ray CT provides more intuitive visualization of damage geometry and volumetric features. The combination of the two effectively compensates for the limitations of each individual technique, significantly reducing false detections and improving the reliability of damage identification.

Meanwhile, data-driven approaches have gradually become a research focus. With the rapid development of deep learning, convolutional neural networks (CNNs), recurrent neural networks (RNNs), and long short-term memory (LSTM) networks have been widely applied to ultrasonic signal analysis. These methods can automatically extract temporal, spectral, and time–frequency features, thereby overcoming the limitations of manually engineered features. Previous studies have employed CNNs to classify ultrasonic B-scan or guided wave images for identifying delamination and debonding damage in composites, achieving high accuracy levels of 90%–95% [6]. Ding et al. [7] reported a deep learning model based on LSTM networks

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combined with guided wave signals, which enabled the prediction of interfacial damage during fatigue loading of composites and identified early-stage stiffness degradation trends.

A more forward-looking development is the emergence of physics–data fusion models. Researchers have begun integrating interfacial spring models with neural networks, using physical models to constrain the network training process and thereby enhance generalization capability. This physics-informed machine learning approach has demonstrated stable performance even under small-sample conditions and is considered a promising direction for the future of data-driven methods.

However, the widespread adoption of multimodal and data-driven approaches still faces several challenges. On one hand, data acquired from different sensors often vary in dimension and scale, making data fusion algorithms complex and difficult to generalize. On the other hand, deep learning models heavily rely on large-scale labeled datasets and often suffer from limited interpretability. Consequently, researchers have widely emphasized the need to establish standardized datasets and evaluation metrics to facilitate the practical implementation of such methods in engineering applications.

4. Optimization of Inversion Techniques

During the 2010s, research on inversion methods advanced rapidly, driven by innovations in algorithms and computational acceleration. Traditional least-squares-based inversion approaches often suffer from high computational cost and slow convergence, whereas modern optimization algorithms-such as conjugate gradient, genetic algorithms, and Bayesian inference-have been introduced to improve efficiency and robustness. Chen et al. [8] proposed a parameter estimation method that combines a nonlinear Hanning-windowed chirp model with a genetic algorithm for the inversion of Lamb wave signals. Even under strong noise conditions, this method can stably extract multiple parameters, demonstrating the robustness of genetic algorithms in ultrasonic inversion applications.

Advancements in computational resources have also been a major driving force. The introduction of GPU acceleration and parallel computing has reduced the computational time of ultrasonic inversion from several hours to just a few minutes, with some applications achieving near real-time processing [9]. This progress has created favorable conditions for online inspection and process monitoring. For instance, in aerospace manufacturing, researchers have demonstrated GPU-based real-time inversion systems capable of dynamically evaluating interfacial quality during the composite layup process [10].

Nevertheless, the widespread application of inversion techniques still faces several challenges. High-precision models often involve numerous parameters, which can easily lead to ill-posed inversion problems. Moreover, discrepancies between model assumptions and experimental conditions may introduce systematic errors into the inversion results. Therefore, achieving an optimal balance between model accuracy and computational efficiency remains a critical issue in this field.

5. Detection of Weak Interfaces and Early-Stage Damage

In the late 2010s, increasing research attention was devoted to the highly sensitive detection of weak interfaces and micro-scale damage. Traditional ultrasonic techniques are effective in identifying large-scale debonding but often struggle to detect subtle degradation or early-stage interfacial cracking. To address this limitation, researchers have employed high-frequency, nonlinear, and phase-sensitive ultrasonic methods.

High-frequency ultrasonics can enhance spatial resolution, enabling the detection of micron-scale cracks or degradation. Previous studies have shown that high-frequency (tens to

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hundreds of MHz) acoustic microscopy or ultrasonic imaging can resolve early signs of delamination or debonding at CFRP interfaces. However, due to the strong attenuation of high-frequency ultrasound in CFRP materials, the penetration depth remains limited, making it challenging to inspect components with substantial thickness [11].

Nonlinear ultrasonic methods, which analyze harmonic components or waveform distortions, are highly sensitive to the nonlinear responses of interfaces. Studies have shown that weak interfaces exhibit nonlinear acoustic characteristics under high stress or cyclic loading, and such signals can often be detected before the appearance of macroscopic cracks [12]. For example, Shui et al. [13] observed during fatigue testing of adhesively bonded composite joints that nonlinear ultrasonic parameters-such as harmonic components-can reflect damage evolution prior to the formation of visible cracks, demonstrating significantly higher sensitivity than conventional linear ultrasonic indicators.

In addition, phase and time–frequency analysis methods have been introduced for the detection of weak interfaces. By monitoring subtle variations in wave velocity or phase delay, researchers can capture early indicators of damage even under noisy conditions [14]. This approach is particularly well suited for long-term structural health monitoring and can serve as an effective early-warning mechanism.

6. Expansion of Application Scenarios

At the application level, the 2010s witnessed the cross-sector expansion of ultrasonic interface characterization technologies. In the wind energy industry, researchers developed online inspection systems based on guided waves and laser ultrasonics to detect early debonding in adhesive layers, thereby preventing catastrophic failures during service [15]. In the automotive industry, ultrasonic inversion techniques have been applied to quality control in the manufacturing of carbon fiber structural components, ensuring the safety and reliability of lightweight designs [16].

The civil engineering field has likewise benefited from these advancements. Researchers have explored the use of ultrasonic interface inspection for monitoring delamination and environmental aging in composite-reinforced structures such as bridges and tunnel linings [17]. These studies indicate that ultrasonic techniques are not limited to small-scale specimens or laboratory environments but are increasingly being applied to the long-term health monitoring of large-scale infrastructure systems.

However, large-scale applications also present significant challenges: complex structures often produce pronounced multipath effects, increasing the difficulty of signal interpretation; moreover, variations in ambient temperature and humidity, background noise, and coupling instability in field environments can all affect detection accuracy [18]. Consequently, researchers have widely emphasized the importance of integrating data-driven approaches with standardized inspection procedures to enhance field adaptability and ensure the comparability of results.

7. Conclusion

As the most critical yet weakest structural unit within composite materials, the fiber–matrix interface largely determines the material's mechanical response and service reliability. This paper systematically reviewed the development of ultrasonic characterization techniques for fiber–matrix interfaces over the past decade, focusing on recent advances in the integration of laser ultrasonics and guided waves, multimodal fusion and data-driven approaches, optimization of inversion techniques, highly sensitive detection of weak interfaces and early-stage damage, and the expansion of engineering applications. Overall, research since the 2010s

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has facilitated the transformation of ultrasonic interface characterization from laboratory investigations to practical engineering applications, evolving from single-signal analysis toward multimodal and intelligent integration. As a result, the technological framework has become increasingly mature, and the range of application scenarios continues to expand.

First, in terms of inspection techniques, the integration of laser ultrasonics and guided wave methods has enabled non-contact, large-area, and high-efficiency interface detection, providing a feasible approach for rapid screening of complex structures. This technology eliminates the instability caused by coupling agents and enhances sensitivity to specific interfacial depths through mode control, making it a promising direction for the inspection of aerospace and wind turbine components.

Second, multimodal fusion and data-driven approaches have overcome the information limitations of traditional ultrasonic inspection. By integrating multi-source data-such as ultrasound, CT, infrared thermography, and eddy current testing-and incorporating deep learning models, these methods achieve automated identification and quantitative analysis of interfacial damage. In particular, the emergence of physics-informed machine learning has introduced a new paradigm for achieving stable inversion under small-sample conditions, representing a cutting-edge trend in the field.

Third, the optimization of inversion algorithms and the acceleration of computation have significantly improved the real-time capability and robustness of interface parameter identification. Modern optimization algorithms, together with GPU-based parallel computing, have reduced the duration of complex inversion processes from hours to minutes or even seconds, laying the groundwork for online quality monitoring and in-process inspection.

Fourth, to address the challenge of detecting weak interfaces and early-stage damage, high-frequency, nonlinear, and phase-sensitive ultrasonic methods have demonstrated excellent sensitivity and predictive capability. These approaches enable the identification of damage prior to macroscopic crack formation, providing crucial support for service life prediction and structural health monitoring.

Finally, the expansion of engineering applications marks the transition of this technology from laboratory validation to industrial implementation. Ultrasonic inspection systems have been successfully demonstrated in the wind energy, aerospace, automotive, and civil engineering sectors, showing strong adaptability and scalability. However, challenges such as multipath effects in complex structures, environmental interferences, and limited algorithm generalization remain key bottlenecks hindering large-scale industrial deployment.

Overall, ultrasonic characterization of fiber–matrix interfaces has evolved from merely “detecting visible defects” to “quantitatively identifying and predicting performance,” progressively becoming a key tool for the structural integrity assessment and service life prediction of composite materials. Looking ahead, future research in this field can be further advanced along the following directions:

(1) Multiscale modeling and multiphysics coupling: Establishing links between microscopic damage mechanisms and macroscopic structural responses to correlate local interfacial parameters with overall structural performance, thereby providing a more reliable theoretical basis for the life prediction of composite materials.

(2) Physics–data fusion for intelligent inversion: Integrating acoustic propagation models with machine learning algorithms and introducing physical constraints to enhance model interpretability and generalization, ultimately constructing a self-learning inversion framework for interface characterization.

(3) Integration of multimodal fusion and digital twin technologies: Combining ultrasonic inspection results with multi-source data such as X-ray CT and infrared thermography, and

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coupling them with digital twin models to enable real-time updating of interfacial states and prediction of degradation processes.

(4) Real-time and automated inspection: Leveraging GPU acceleration, edge computing, and intelligent scanning platforms to achieve online monitoring and automated inspection for both production lines and in-service structures.

(5) Standardization and industrial implementation: Developing unified datasets, experimental protocols, and evaluation systems, while promoting cross-industry collaboration to accelerate the standardization and large-scale adoption of ultrasonic interface characterization technologies.

In summary, ultrasonic characterization of fiber–matrix interfaces is undergoing a critical transition from methodological innovation to engineering implementation. With the continued integration of artificial intelligence, digital twin technology, computational acoustics, and multiphysics modeling, the coming decade is expected to bring significant breakthroughs in precision, intelligence, and standardization—providing a solid technological foundation for the safety monitoring and full life-cycle management of composite material structures.

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