ISSN: 2688-8645

Recent Advances in Characterizing the Interfacial Mechanical Properties of Composites based on Ultrasonic Inversion

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Abstract

In response to the growing demand for composite materials with high specific strength, high specific stiffness, and lightweight structural characteristics, this paper systematically reviews the development and research progress of ultrasonic characterization techniques for fiber–matrix interfaces. The mechanical and durability properties of composites are largely governed by the interfacial bonding quality and its evolution mechanisms. However, interfacial damage is often concealed within the material, highlighting the urgent need for quantitative and nondestructive monitoring approaches. First, the paper reviews the emergence and development of the Scanning Acoustic Microscope in the 1970s and elaborates on its pioneering role in revealing interfacial microstructures and early-stage debonding phenomena. Subsequently, it focuses on the quantitative studies since the 1990s based on the imperfect interface spring model, including the introduction of normal and tangential stiffness parameters (KN and KT), the development of reflection/transmission inversion methods, and the establishment of spectrum–angular spectrum analysis techniques. These advances enabled a paradigm shift in interfacial characterization—from mere visualization to quantitative evaluation. In the 21st century, research has further evolved toward refined modeling, optimized inversion algorithms, and engineering-oriented applications, leading to the formation of multi-angle, multi-frequency, and multimodal integrated detection frameworks. By integrating signal processing, finite element simulation, and machine learning, the accuracy and stability of interface parameter inversion have been significantly enhanced. Finally, the paper summarizes the major challenges in this field, including model ill-posedness, adaptability under complex environments, and difficulties in data fusion. It also envisions future developments toward intelligent, real-time, and multi-physics-coupled characterization approaches.

Keywords

Composites; Fiber–Matrix Interface; Ultrasonic Characterization; Inversion Algorithms; Nondestructive Testing.

1. Introduction

Driven by the demand for high specific strength, high specific stiffness, and lightweight structures, composite materials have been extensively applied in load-bearing components across aerospace, wind energy, and transportation industries. Their macroscopic load-bearing capacity and long-term durability largely depend on the properties and evolution mechanisms of the fiber–matrix interface or interphase region. Insufficient interfacial bonding, contact degradation, and environmental aging processes often occur prior to bulk failure, potentially triggering typical failure modes such as debonding, delamination, microcrack propagation, and fiber pull-out. Such damage weakens the effective load transfer from the matrix to the fibers, resulting in stiffness reduction, strength degradation, and shortened fatigue life. Under full life-

ISSN: 2688-8645

cycle service conditions, interface-dominated damage often remains hidden within the material, with evolution scales ranging from the microscale to the structural level. In the absence of repeatable and quantitative nondestructive monitoring techniques, the assessment of structural integrity and the prediction of service life become highly uncertain. Studies have shown that many "early indicators" of composite reliability originate from the micromechanical responses of the interfacial layer rather than from macroscopic crack formation. This insight underscores the importance of mechanism identification and state perception at the interface level.

Among various characterization techniques, ultrasonic methods have attracted widespread attention due to their combined advantages of penetration depth, high sensitivity, and adaptability for in-situ applications. Ultrasonic waves are highly sensitive to stress–strain characteristics and interfacial contact conditions (bonded or debonded states). Variations in amplitude, phase, and frequency spectra can be utilized to reveal subtle changes in the interfacial stiffness. Based on the imperfect interface spring model, researchers have introduced normal and tangential stiffness parameters (KN and KT) to characterize the interfacial bonding state. By analyzing reflected and transmitted ultrasonic signals, the corresponding interfacial mechanical parameters can be inverted, enabling a quantitative description of interfacial behavior.

This paper reviews the evolution of ultrasonic characterization techniques for fiber–matrix interfaces, from the emergence of the Scanning Acoustic Microscope (SAM) in the 1970s to the maturation of inversion algorithms in the early 21st century. It focuses on the advancements in interfacial modeling, quantitative inversion methodologies, and their engineering applications. The paper further summarizes the advantages, limitations, and developmental trends at each stage, thereby laying a foundation for future research in multimodal and intelligent characterization.

2. Emergence of the Scanning Acoustic Microscope

The ultrasonic characterization of composite interfaces can be traced back to the early 1970s. At that time, research efforts primarily focused on overcoming the spatial resolution limitations of conventional ultrasonic testing, aiming to extend its application from detecting macroscopic structural defects to analyzing interfacial phenomena at the microscopic scale [1]. Against this backdrop, Lemons and Quate at Stanford University developed the Scanning Acoustic Microscope (SAM), which, for the first time, achieved micron-scale imaging of solid materials using high-frequency focused ultrasound [2]. Their pioneering work established both the theoretical and experimental foundations of acoustic microscopy and is widely regarded as the starting point for ultrasonic investigations of composite material interfaces.

The core concept of the Scanning Acoustic Microscope (SAM) lies in focusing high-frequency ultrasonic waves into a minute acoustic spot using an acoustic lens, followed by point-by-point scanning of the sample surface to reconstruct two-dimensional or even three-dimensional images of the material's interior from the reflected echo signals. Compared with conventional industrial ultrasonic testing operating at megahertz frequencies, SAM typically employs much higher frequencies ranging from several tens to hundreds of megahertz, thereby achieving micrometer- or even submicrometer-level resolution. This capability enabled, for the first time, the visualization of interfacial bonding conditions, voids, inclusions, and microcracks. In composite material systems, SAM has revealed the characteristic features of the fiber–matrix interfacial region, including local debonding, rough contact surfaces, and impurity distributions, providing direct evidence for understanding how interfacial properties influence the overall mechanical performance of composites.

The pioneering work of Lemons and Quate quickly attracted significant attention from subsequent researchers. Takeda and colleagues[3]applied the Scanning Acoustic Microscope (SAM) to fiber-reinforced composites, using in-situ imaging to directly observe the initiation and propagation of microscopic interfacial damage. Their study demonstrated the unique advantages of SAM in revealing interfacial geometries and early-stage damage evolution. Such explorations promoted the transition of SAM from a laboratory verification tool to an engineering-relevant research technique, establishing it as one of the essential methods for evaluating interfacial quality. Meanwhile, Kushibiki and Chubachi systematically summarized the physical principles of SAM and further optimized the design of acoustic lenses and transducers, enabling high-resolution imaging over a broader frequency range [4].

Beyond composite materials, the applications of the Scanning Acoustic Microscope (SAM) in other fields have likewise contributed to the maturation of this technique. In the microelectronics industry, SAM has been widely employed to detect delaminations, voids, and microcracks in chip packages and solder joints, making it one of the standard tools for quality assurance. In the biomedical field, Atalar and collaborators utilized SAM to achieve high-resolution imaging of cells and soft tissues, demonstrating the unique advantages of ultrasound in biological sample analysis. These interdisciplinary applications have not only expanded the practical scope of SAM but also provided valuable theoretical and experimental insights for its further adoption in the interfacial characterization of composite materials.

However, although the Scanning Acoustic Microscope (SAM) provided an unprecedented means for interfacial micro-imaging, it also exhibited notable limitations at the time. First, the use of high-frequency ultrasound led to significant acoustic attenuation within materials, thereby restricting the penetration depth and making SAM more suitable for observing thin specimens or near-surface regions. Second, the imaging results were primarily qualitative—while capable of revealing the presence and distribution of defects, SAM was unable to directly quantify interfacial mechanical parameters such as stiffness or bonding strength. In addition, the high cost and operational complexity of the equipment limited its application during the 1970s and 1980s mainly to laboratory-scale research.

Overall, the advent of the Scanning Acoustic Microscope (SAM) represented a significant breakthrough in the spatial resolution of ultrasonic technology, transforming interfaces from being “invisible” to “imaginable.” SAM not only demonstrated great potential in the characterization of composite material interfaces but also achieved successful applications in fields such as electronic packaging and biomedical imaging. Although research during this period was largely confined to qualitative imaging, SAM established a crucial foundation for subsequent quantitative ultrasonic characterization based on reflection/transmission analysis and interfacial modeling. With the introduction of the interface spring model and inversion algorithms in the 1990s, the focus of research gradually shifted from merely “visualizing” the interface to “quantifying” it, marking the onset of a new stage in ultrasonic interface characterization.

3. Quantitative Ultrasonics for Fiber–Matrix Interfaces

With the advancements in material science and ultrasonic technology during the 1990s, the characterization of composite interfaces gradually evolved from mere “imaging” to “quantitative analysis.” Researchers aimed not only to reveal the presence of interfacial defects but also to determine interfacial mechanical parameters—such as stiffness and bonding strength—through the inversion of ultrasonic signals. This transformation is regarded as a milestone in the development of nondestructive testing for composite materials, directly driving the subsequent engineering-oriented applications.

ISSN: 2688-8645

3.1. Introduction of Interfacial Stiffness and Elastic Parameters

In the early 1990s, Yen and Tittmann, in their studies on carbon–carbon composites, first proposed the concept of quantitatively extracting interfacial mechanical properties from ultrasonic reflection and transmission signals [5]. They demonstrated that the interfacial shear and normal stiffness could be inversely determined from the amplitude and phase relationships of ultrasonic echoes. This breakthrough extended the role of ultrasonics from merely "visualizing defects" to "quantifying interfacial mechanical parameters." Subsequently, Rokhlin and colleagues applied this concept to metal–ceramic and polymer–composite systems, demonstrating its broad applicability across diverse material interfaces [6].

The significance of these studies lies in the fact that, for the first time, ultrasonic testing results were correlated with the overall performance of composite materials. For example, a reduction in interfacial stiffness often indicates a shortened fatigue life or the accumulation of early-stage damage. However, such investigations remained constrained by experimental conditions—high-frequency ultrasonic signals require strict control over sample preparation, interfacial flatness, and coupling conditions—thus limiting their applications primarily to laboratory-scale research.

3.2. Spring Model and Inversion Methods

To achieve a systematic description of interfacial parameters, researchers such as Karpur and Matikas proposed the imperfect interface spring model, in which the interfacial bonding state is characterized by a normal stiffness (KN) and a tangential stiffness (KT) [7]. This model assumes that the interface can be equivalently represented as a "spring layer" capable of transmitting stress while permitting limited relative displacement between adjoining materials. By measuring the amplitude and phase characteristics of reflected and transmitted ultrasonic waves, the values of (KN) and (KT) can be inversely determined.

The primary advantage of this model lies in its simplicity and clear physical interpretability, which quickly established it as a fundamental tool in ultrasonic interface research. The Rokhlin research group made significant extensions to this model by introducing a frequency-response-based inversion approach that enabled the extraction of interfacial stiffness over a broad frequency range and the tracking of its evolution during degradation processes [8]. For instance, in carbon fiber–reinforced epoxy composites, the inversion results revealed a gradual decrease in interfacial stiffness under fatigue loading, which showed excellent agreement with corresponding mechanical test observations.

However, the spring model also involves certain simplifications. It typically assumes the interface to be an ideal, homogeneous layer, which makes it insufficient to fully represent complex interfacial conditions such as surface roughness, heterogeneity, or the presence of multilayer coatings. Consequently, studies in the late 1990s began to explore more sophisticated modeling approaches and advanced inversion algorithms to better capture the real interfacial behavior.

3.3. Spectrum and Angular Spectrum Analysis

Alongside the progress in quantitative characterization, spectral and angular spectrum techniques were gradually introduced into interfacial studies. Rokhlin and colleagues proposed analyzing the frequency-dependent reflection coefficients to assess interfacial conditions, thereby determining the variation of interfacial stiffness with frequency [9]. This approach enables the investigation of energy dissipation and scattering characteristics of the interface under different frequencies, making it particularly suitable for characterizing interfacial aging and fatigue processes.

Meanwhile, the angular spectrum reflection technique also underwent significant development. By varying the ultrasonic incident angle and systematically measuring the reflection

ISSN: 2688-8645

characteristics, this method enables the extraction of information related to interfacial anisotropy and heterogeneity. For fiber-reinforced composites, it effectively distinguishes differences in interfacial bonding among regions with varying fiber orientations. The main advantage of the angular spectrum technique lies in its high sensitivity to localized defects; however, it requires stringent experimental setup control and complex data processing, and thus has been primarily applied in laboratory-scale verification studies.

3.4. Early Engineering Applications

With the gradual maturation of theoretical frameworks and analytical methods, quantitative ultrasonic characterization began to see preliminary engineering applications in the 1990s. Organizations such as NASA introduced this technique into the quality control and in-service monitoring of composite components used in spacecraft, primarily focusing on evaluating the interfacial bonding integrity of laminated structures [10]. For instance, in spacecraft skins and honeycomb sandwich panels, ultrasonic inversion methods were able to distinguish between "well-bonded" and "weakly bonded" interfaces, providing valuable data support for production quality assurance.

The automotive and civil engineering sectors also began to show interest in this approach. Some studies explored the application of ultrasonic inversion techniques for assessing interfacial quality in wind turbine blades. Although the inspection speed and stability at that time were not yet sufficient to fully meet industrial requirements, these early efforts successfully demonstrated the feasibility of quantitative ultrasonics for evaluating complex engineering structures.

In summary, research conducted during the 1990s marked a pivotal transition from "interfacial imaging" to "interfacial quantification." Through the introduction of interfacial stiffness parameters, the spring model, and spectral/angle spectrum analyses, ultrasonic techniques advanced from merely revealing interface defects to quantitatively characterizing interfacial mechanical properties and correlating them with macroscopic behavior. However, several challenges persisted during this period: (1) **Model simplification** — the spring model could not adequately account for multilayer structures, surface roughness, or material anisotropy; (2) **Experimental complexity** — stringent requirements on sample preparation, interfacial flatness, and coupling conditions limited broader applicability; and (3) **Limited field adaptability** — the techniques were primarily restricted to laboratory and small-scale validation, making direct industrial deployment difficult. Consequently, improving adaptability while maintaining quantitative accuracy became a key research objective entering the 21st century. With the advancement of computational power and acoustic modeling, studies gradually transitioned toward more sophisticated inversion algorithms and engineering-oriented practices, laying the groundwork for the next stage of mature applications.

4. Maturation of Quantitative Characterization and Inversion

Entering the 21st century, ultrasonic characterization of fiber–matrix interfaces reached a stage of relative maturity. Unlike the 1990s, which primarily focused on model formulation and experimental validation, research in this period shifted toward refining interfacial models, optimizing inversion algorithms, and expanding engineering applications. By integrating advanced signal processing, numerical simulation, and high-performance computing, ultrasonic characterization techniques not only enabled the identification of interfacial defects but also allowed for the quantitative evaluation of damage evolution, demonstrating strong potential for application in real engineering environments.

4.1. Expansion and Refinement of the Interfacial Spring Model

Building upon the "imperfect interface spring model," the Rokhlin research group proposed a dual-interface spring model that further accounted for interfacial thickness effects, surface roughness, and multilayer structural characteristics [11]. Compared with the conventional single-interface model, the dual-interface approach provided more accurate stiffness inversion results when analyzing coated, adhesive, and multilayer composite structures. This development significantly enhanced the model's adaptability to complex engineering interfaces. Subsequently, Baltazar and Rokhlin combined spectral and angular spectrum analyses to propose a multi-angle, multi-frequency inversion algorithm [12]. By systematically measuring reflection coefficients across various incident angles and frequencies, they were able to retrieve the frequency-dependent evolution of both normal and tangential interfacial stiffness. This method not only improved the stability of interfacial parameter extraction but also enabled the distinction between different damage mechanisms, such as debonding versus degradation. For instance, in metal–ceramic adhesive structures, the approach revealed a gradual decline in interfacial stiffness under thermal cycling, which showed strong agreement with microstructural observations.However, the refinement of such models also introduced new challenges. The increasing number of parameters made the inversion process more ill-posed and susceptible to noise interference. Moreover, multi-angle experiments increased testing complexity in practical applications. Consequently, researchers began exploring the integration of numerical simulation with optimization algorithms to enhance the robustness and stability of the inversion process.

4.2. Engineering Development of Inversion Techniques

In the early 21st century, with the rapid increase in the use of composite materials in aerospace applications, ultrasonic inversion techniques began to be adopted for industrial quality control and structural health monitoring (SHM). NASA applied interfacial stiffness inversion methods to evaluate the quality of spacecraft skins, wings, and honeycomb sandwich structures [13]. Studies showed that stiffness parameters are highly sensitive to early-stage debonding and can serve as key indicators for determining whether components require repair or decommissioning. The European Space Agency (ESA) also implemented ultrasonic inversion in the inspection of composite components for satellites, demonstrating broad institutional recognition of the technique [14].In the automotive and energy sectors, ultrasonic inversion has been explored for quality control of wind turbine blades and automotive composite components. For example, during static load testing and SHM programs for wind turbine blades, researchers employed ultrasonic and other nondestructive testing (NDT) methods to monitor the state of adhesive and bonded interfaces, aiming to detect early adhesive failures. Although the inspection speed and level of automation remain limited, these studies marked an important step in transitioning ultrasonic inversion from laboratory research to on-site industrial practice.These applications highlight the advantages of ultrasonic inversion—non-destructive, quantitative, and highly sensitive—while also revealing several challenges that remain unresolved. These include uncertainties in coupling conditions under complex field environments, the influence of temperature and humidity, and the need for efficient large-scale data processing.

4.3. Development and Application of Multimodal Approaches

As research progressed, scholars recognized that a single ultrasonic method has inherent blind spots when applied to complex structures. Consequently, multimodal approaches emerged, integrating ultrasonics with other nondestructive testing (NDT) techniques such as X-ray computed tomography (CT), infrared thermography, and eddy current testing to achieve complementary characterization. Katunin *et al.* [15] proposed combining ultrasonic inspection with X-ray CT for defect identification in multilayer composite structures. Their study showed that ultrasonics exhibits higher sensitivity in detecting interfacial debonding and interlaminar mechanical conditions, whereas X-ray imaging provides superior geometric and volumetric defect characterization. The combination of these modalities significantly enhanced the completeness and reliability of defect diagnosis.In addition, multimodal methods have been increasingly applied to the characterization of coating–substrate interfaces. Some studies have integrated ultrasonics with infrared or thermal imaging to monitor delamination and interfacial separation processes in thermal barrier coatings (TBCs) under thermal cycling or isothermal aging conditions. For instance, Chen *et al.* [16] employed ultrasonic testing to detect delamination in TBC systems and estimate material parameters such as Young's modulus; Franke *et al.* [41] [17]used mid-infrared reflectance imaging to monitor delamination progression; and Qu *et al.* [18]proposed an ultrasonic–infrared thermography hybrid technique that demonstrated the complementarity of the two detection modalities in damage identification.Although multimodal approaches have markedly improved detection accuracy and diagnostic reliability, their limitations remain significant—high equipment costs, complex data fusion algorithms, and incomplete quantitative correlations among different physical parameters continue to restrict their widespread industrial adoption.

4.4. Enhanced Sensitivity to Weak Interfaces and Early-Stage Damage

Another important research direction in the 2000s was improving the detection capability for weak interfaces and early-stage damage. Traditional ultrasonic techniques primarily focused on pronounced debonding or delamination, whereas subtle interfacial degradation and microcracking can often begin to compromise structural integrity at much earlier stages. Rokhlin *et al.* [19]employed high-frequency ultrasonics combined with spectral inversion to successfully capture the initiation of microcracks and early delamination phenomena in composite materials. This method tracks small phase variations to monitor the gradual reduction in interfacial stiffness, making it a valuable tool for preventive maintenance.In addition, nonlinear ultrasonic techniques began to emerge. Studies have shown that weak interfaces exhibit nonlinear responses—such as higher-order harmonics or waveform distortion—under high-frequency or large-strain excitation, features that are particularly sensitive to early-stage damage. Although nonlinear ultrasonics impose stringent experimental requirements, their potential for monitoring minute damage has attracted increasing attention and is considered a promising approach for early detection and health assessment of composite interfaces.

4.5. Innovations in Signal Processing and Data Analysis

During the 2000s, advancements in computational power led to rapid progress in ultrasonic signal processing techniques. Fast Fourier Transform (FFT), Short-Time Fourier Transform (STFT), and wavelet transform were widely employed for time–frequency analysis of ultrasonic signals, enabling more precise extraction of interfacial damage features. Statistical methods such as Principal Component Analysis (PCA) and pattern recognition techniques were also utilized to reduce noise effects and enhance feature separability.Meanwhile, finite element analysis (FEA) became increasingly integrated with inversion algorithms, providing strong support for modeling complex interfacial structures. Numerical simulations were used to generate virtual ultrasonic datasets for validating and optimizing inversion algorithms—an approach particularly valuable when experimental data were limited or unavailable.This period also saw the early adoption of machine learning in ultrasonic data interpretation. Simple neural networks and Support Vector Machines (SVMs) were applied for interfacial damage classification, demonstrating the preliminary potential of intelligent data-driven analysis in ultrasonic characterization.

Overall, research conducted during the 2000s brought ultrasonic characterization of fiber–matrix interfaces into a relatively mature stage. Through model refinement, inversion

ISSN: 2688-8645

optimization, multimodal integration, and innovations in signal processing, researchers significantly enhanced the quantitative assessment and early detection capabilities for interfacial damage. However, several challenges also emerged during this period: the increasing model complexity intensified the ill-posed nature of inversion problems; practical engineering applications remained constrained by experimental conditions and data processing efficiency; and although multimodal approaches improved diagnostic accuracy, they came with high costs and algorithmic complexity. Consequently, researchers gradually shifted their focus toward improving engineering adaptability and enhancing inspection efficiency for real-world applications.

5. Summary and Outlook

The fiber–matrix interface is a critical region that governs the service performance and lifespan of composite materials, with its mechanical response and damage evolution exerting profound multiscale effects on overall structural reliability. Reviewing the development over the past half century, ultrasonic characterization techniques for composite interfaces have undergone continuous evolution—from qualitative microscopic imaging to quantitative inversion modeling, and eventually to multimodal and intelligent characterization.The emergence of the Scanning Acoustic Microscope (SAM) first enabled the visualization of interfacial structures, establishing both the experimental and theoretical foundations for subsequent studies. The development of the imperfect interface spring model and its associated inversion algorithms marked the transition of ultrasonic testing from merely “visualizing” the interface to “quantifying” it. Entering the 21st century, driven by advances in computational acoustics, signal processing, and machine learning, ultrasonic interfacial characterization has achieved remarkable improvements in accuracy, adaptability, and breadth of application.

However, several key scientific and engineering challenges remain to be addressed. First, existing interfacial models are still overly simplified when describing multilayered, rough, or heterogeneous structures, necessitating the development of multiscale and multiphysics-coupled modeling frameworks. Second, uncertainties in coupling conditions under field environments, the effects of temperature and humidity, and the inversion of signals from complex curved components continue to pose major bottlenecks for engineering applications. In addition, the extraction of high-dimensional ultrasonic features and the establishment of interpretable models still require deeper integration with artificial intelligence and big data analytics.

Future research can focus on:

(1) Developing high-fidelity interfacial models and physics-driven inversion algorithms to achieve accurate identification of complex interfaces;

(2) Establishing multimodal data fusion systems that combine ultrasonic, infrared, X-ray, and electromagnetic signals for comprehensive interfacial damage diagnosis;

(3) Exploring intelligent detection and predictive frameworks based on machine learning and digital twins to provide a scientific foundation for full-lifecycle health monitoring and service life assessment of composite materials.

Overall, ultrasonic characterization of fiber–matrix interfaces is transitioning from the stage of experimental validation to a new era of intelligent, real-time, and systematic evaluation. Its ongoing development not only deepens the understanding of interfacial micromechanical mechanisms but also provides essential support for ensuring the safe service performance and optimization of composite material structures.

ISSN: 2688-8645

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