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DAMAGE MONITORING OF FIBER REINFORCED COMPOSITES BASED ON CONTINUOUS WAVELET TRANSFORM

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Fiber reinforced composites (FRCs) have emerged as pivotal materials in various industries, such as aerospace, automotive, and civil engineering, due to their exceptional strength-to-weight ratio and design flexibility. However, the complex internal structure and susceptibility to damage – such as matrix cracking, fiber breakage, and delamination – pose significant challenges for their structural integrity and performance. The early detection and monitoring of damage in FRCs are paramount for ensuring safety and reliability [1]. Recently, advanced signal processing techniques, notably the Continuous Wavelet Transform (CWT), have gained recognition for their effectiveness in monitoring damage in composite materials [2].

The Continuous Wavelet Transform is a powerful mathematical tool that allows for time-frequency analysis of signals. Unlike simpler techniques such as Fourier Transform, which provides information solely in the frequency domain, CWT retains temporal information, making it especially useful for transient signals – like those generated during composite damage.

The CWT of a signal *x*(t) can be mathematically expressed as

$$W(a,b)=a^{-0.5}\int_{-\infty}^{\infty} x(t)\psi^*[(t-b)/a]dt, \qquad (1)$$

where W (a, b) is the wavelet coefficient ; ψ is the analyzing wavelet function; a is the scale; b is the translation, and symbol '' denotes the complex conjugate.*

The choice of the mother wavelet function ψ is crucial and hinges on the nature of the signal being analyzed.

FRCs can develop various damage mechanisms under loading, including micro-cracking, fiber pull-out, and delamination, each contributing to degradation in material properties. These damage modes often produce stress waves that can be captured using sensors like piezoelectric transducers [3]. The resultant signals contain rich information regarding the state of the material, including higher frequency components that correlate with nascent damage. By utilizing CWT, one can decompose these signals into their constituent frequencies, revealing transient changes in the time-frequency domain associated with damage initiation.

The primary steps in monitoring damage in FRCs using CWT involve: A. Signal Acquisition: Capture the data associated with structural responses using sensors installed on the composite material. B. Wavelet Transform: Compute the CWT of the acquired signals. This provides a two-dimensional representation, showcasing how the signal's frequency content evolves over time. C. Feature Extraction: Analyze the wavelet coefficients to identify features indicative of damage. Changes in the energy distribution of wavelet coefficients can provide clues about the onset and progression of damage. D. Detection Algorithm: Develop algorithms based on statistical methods or machine learning to classify the state of the material (healthy/damaged) based on extracted features. To quantify damage, one useful metric is the energy of the wavelet coefficients. If we denote the wavelet transform of the signal as $W(a, b)$, the energy of the wavelet coefficients can be expressed as

$$E = \sum_{a} \sum_{b} |W(a,b)|^2 , \qquad (2)$$

where E represents the energy of the wavelet coefficients. Monitoring changes in the total energy between pre-damage and post-damage states can serve as an effective indicator of damage severity.

Recent studies illustrate the application of CWT in the damage monitoring of FRCs. In one example, a composite beam subjected to mechanical loading was monitored using surface-mounted sensors. Damage was induced gradually, and CWT was performed on the collected sensor signals. The results highlighted distinct changes in the energy distribution of the wavelet coefficients correlating to the onset of visible damage, validating the efficacy of CWT in detecting damage before it reached critical levels. Another study focused on the effects of environmental factors, such as temperature variations and humidity, on the damage detection capabilities of CWT. It was found that while these factors could influence signal characteristics, the wavelet technique remained robust in distinguishing between normal operational signatures and those indicating damage, effectively demonstrating the method's resilience.

Summary and conclusions. The continuous wavelet transform (CWT) represents a significant advancement in the field of damage monitoring for fiber reinforced composites. Its ability to analyze time-varying signals allows for the early detection and characterization of damage phenomena that might otherwise go unnoticed. By extracting relevant features from the wavelet coefficients, researchers can establish a solid framework for assessing the health of composite structures in real-time. In conclusion, the integration of CWT into damage monitoring systems not only enhances the reliability of fiber reinforced composites but also contributes to the overarching goals of structural health monitoring. Future research suggests the continued exploration of optimized wavelet functions and machine learning techniques to further improve the accuracy and efficiency of damage detection frameworks. The long-term benefits include enhanced safety, extended service life, and reduced maintenance costs for critical infrastructure utilizing composite materials.

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