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MULTIVARIABLE DAMAGE ANALYSIS FOR FIBER-REINFORCED COMPOSITES

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Abstract. *Damage detection and assessment in carbon-fiber-reinforced polymer (CFRP) composites is challenging because of their anisotropic and heterogeneous nature. Their damage progression is complex, involving multiple failure modes like matrix cracking, fiber-matrix debonding, and delamination. Acoustic emission (AE) is an effective non-destructive evaluation (NDE) technique for monitoring the health of composite structures under load. This approach allows for continuous, real-time monitoring throughout the entire loading history of a structure, which is invaluable for understanding the damage evolution process. This research leverages a multiparameter approach to enhance the accuracy of damage analysis using AE. Instead of relying on single descriptors like amplitude or counts, which may not fully capture the complexity of damage, this study integrates multiple acoustic features. The selected features, including the absolute signal level (ASL), initiation frequency, and reverberation frequency, provide a more comprehensive characterization of the acoustic signatures associated with different damage modes. The combination of these features allows for a more robust and detailed description of damage propagation in CFRP single-lap shear joints. To streamline the analysis and identify the most informative features, principal component analysis (PCA), a statistical technique for dimensionality reduction, was applied. The selected features were then subjected to fuzzy c-means (FCM) clustering, a data-clustering algorithm, to group the AE signals into distinct clusters. Each cluster is hypothesized to correspond to a specific damage mechanism, enabling the identification and characterization of different failure modes with greater precision. This method improves the reliability of AE analysis and provides a more nuanced understanding of damage progression in CFRP structures.*

Key words: *acoustic emission, composites, non-destructive evaluation, damage propagation, principal component analysis, fuzzy C-means.*

Introduction.

The acoustic emission (AE) technique is based on detecting and interpreting sound waves caused by rapid internal displacements in a material, which travel at an ultrasonic velocity [1, 2]. The formation and propagation of cracks due to various damage sources are the origins of these acoustic signals. Simply put, when a material undergoes local and irreversible deformation, it releases energy as elastic waves, and the AE method is based on analyzing these waves. The characteristics of these elastic waves are studied in the frequency domain or time-frequency domain using different types of waveform analysis.

Waveform analysis involves the post-processing of acoustic signals after their acquisition. This post-processing can sometimes demand significant computational power and consume a large amount of data storage. In particular, when continuous acoustic signals are studied in their time-frequency domain, the data processing becomes very time-consuming. For these reasons, acoustic signals can be characterized by their energy, peak amplitude, duration, rise time, and many other parameters. These parameters are derived from the acoustic signals and can define the characteristics of the acoustic source.

There is a long-standing debate about which parameters are the most relevant for efficiently describing damage characteristics. The peak amplitude and peak frequency of the waveform are often considered the best parameters for defining the characteristics of the acoustic source. However, in recent years, several researchers have shown that the peak amplitude and peak frequency of the acoustic waveform can be misleading. This is because a single parameter may not fully capture the complexity of the damage event. For instance, the amplitude of an AE signal can be influenced not only by the severity of the damage but also by factors like the distance from the source to the sensor and the material's attenuation properties. Similarly, the peak frequency can be affected by the geometry of the structure and the presence of reflections and scattering. Therefore, relying on these parameters alone may lead to inaccurate interpretations of the damage state. This has led to the development of multiparameter approaches, which integrate a variety of AE features to create a more comprehensive and robust picture of the damage. By analyzing multiple parameters simultaneously, such as the absolute signal level, initiation frequency, and reverberation frequency, researchers can better differentiate between various damage modes, like matrix cracking, fiber-matrix debonding, and delamination [3, 4]. This multiparameter approach provides a more reliable foundation for structural health monitoring and non-destructive evaluation of materials.

Data Clustering Results

The calculation method processed a set of numerical data on scattering on deformations of composites of acoustic signals. The signals were divided into current

(U_{max}) and reference (U_{ref}). The signal ratio was measured in decibels (dB) and could be expressed as:

$$A = 20\,log\left(\frac{U_{max}}{U_{ref}}\right). \tag{1}$$

The average level (ASL_v) for acoustic signals was expressed by the following relationship

$$ASL_V = \frac{1}{T}\int_{t_0}^{t_0+T}|V_i|dt = \frac{1}{N}\sum_{n=1}^{N}|V_i(n)|\ , \tag{2}$$

where N is the total number of discretized signal points; V_i is the amplitude of transient signal; T is the duration of the signal.

The peak frequency of the acoustic emission signal coincided with the frequency of the signals having the maximum amplitude. The analysis of the signal coefficients in their frequency domain was performed using the fast Fourier transform.

These principal components form a symmetric matrix, where the eigenvectors of the matrix constitute its elements. These eigenvectors can be defined as the characteristic vectors of the matrix. They are unique in the sense that they remain directionally invariant under linear transformation by their parent matrix. A data-driven approach was used to analyze key parameters for monitoring defects in reinforced composites. The characteristic parameters were selected for analysis after being reduced using Principal Component Analysis (PCA). Following this, the selected parameters were clustered using the Fuzzy C-Means (FCM) data clustering method. This technique is well-suited for clustering any two-dimensional data, grouping the dataset into a predefined number of clusters. Unlike other clustering methods where each data point belongs exclusively to a single cluster, FCM allows data points to belong to all clusters to a certain degree. The degree of membership is determined by the distance between the data point and the centroid of each cluster. A data point has a higher degree of membership with the cluster that has the closest centroid and a lower degree of membership with the cluster that has the farthest centroid. This fuzzy approach provides a more nuanced and accurate representation of complex data relationships, which is particularly useful for identifying subtle changes in acoustic emission signals associated with different damage mechanisms in composite materials. The process begins by measuring a wide range of acoustic emission features from the material under load, which often includes parameters like amplitude, duration, rise time, and frequency content. Due to the high dimensionality and potential redundancy of this raw data, PCA is a crucial first step. It transforms the original set of variables into a smaller set of uncorrelated principal components, effectively capturing the most significant information in the dataset while eliminating noise and irrelevant data. This not only simplifies the analysis but also enhances its reliability. Once the most informative features are identified, FCM is applied. The algorithm iteratively calculates cluster centers and the membership degree of each data point to these centers until the process converges. This allows for the identification of natural groupings in the data, with each cluster representing a specific type of defect or damage mode, such as matrix cracking or fiber breakage. By assigning each data point a degree of belonging to multiple clusters, FCM accounts for the often ambiguous nature of damage events in composites, where a single acoustic emission signal might be a result of multiple concurrent failure processes. This method thus provides a powerful tool for a more robust and detailed understanding of damage evolution in advanced composite structures.

Summary and conclusions.

The multiparameter acoustic emission approach proved to be an effective method for identifying damage modes in CFRP single-lap shear joints. By combining principal component analysis (PCA) with fuzzy c-means (FCM) clustering, we successfully reduced the complexity of the AE data and identified key features, specifically I-Frequency, R-Frequency, and peak amplitudes, that are most indicative of damage. The subsequent clustering of these features into three distinct groups, each corresponding to different damage mechanisms, allowed for a nuanced understanding of the failure process. By plotting the clustered data against the load-displacement curves of the specimens, we were able to accurately distinguish between critical damage modes, including matrix cracking, interlaminar crack growth, and the initial and final stages of ultimate rupture. This demonstrates that a data-driven approach based on a combination of different AE features provides a more robust and detailed characterization of damage evolution in composites than traditional single-parameter methods. The findings highlight the potential of this technique for real-time structural health monitoring. The future direction of this research involves integrating an in-line fractographic analysis to directly correlate the observed damage modes with their unique AE signatures. This will further validate the effectiveness of our methodology and enable the more reliable and widespread use of acoustic emission for comprehensive damage analysis in various composite structures. This work lays the groundwork for developing more sophisticated and automated systems for assessing the integrity of composite materials.

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