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CLUSTER ANALYSIS OF MECHANICAL DAMAGE IN LAMINATED COMPOSITES

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High values of strength-to-density ratio and specific stiffness determine the wide application of laminated and reinforced composite materials in various industries [1]. However, damage is largely inevitable during processing, preparation or use of composite structures. Certain threats to the safety of composite structures during their operation can be caused by such macroscopic damage modes as matrix cracking, delamination, delamination and rupture of the matrix fiber.

An essential condition for ensuring the safety and reliability of composites is an effective method of damage monitoring. Acoustic emission technology is a widely used tool for online monitoring of the structure's condition [2]. The damage signal is transmitted as an elastic wave with a rapid release of energy, and the signals collected by the sensors are then analyzed by devices to extract characteristic parameters. Due to the complexity and stochastic nature of damage mechanisms in composites, it is necessary to use multi-parameter analysis to process acoustic emission signals to improve the accuracy of damage model identification. Typical acoustic emission parameters include amplitude, rise time, duration, count and energy.

This work uses general unsupervised clustering methods to identify damage patterns in carbon-epoxy composites, including k-means [3]. The computational model records each input vector that corresponds to the cluster center. The correspondence determination procedure is performed on the basis of the Euclidean distance between the cluster center and the input vector, and the membership function values are in the range from 0 to 1. The calculation procedure includes a packet wavelet transform of frequency-time analysis and processing of acoustic signals in a composite material. The non-stationary component of the signals is decomposed into low-frequency and high-frequency parts, which correspond to the approximation and detailing of the local volume of mechanical damage.

Each specific position in the wavelet packet represents a separate frequency band, and the frequency range of each component is calculated using the equation

$$\left[n\frac{1}{2}f_s2^{-i},(n+1)f_s2^{-i}\right], n = 0,1,2,\dots,2^i, \quad (1)$$

where:
f_s is the sampling rate;
n is the decomposition level index;
i is the decomposition level.

The energy of each component of the wavelet transform of acoustic signals can be determined according to the equation

$$E_i^n(t) = \sum_{\tau=t_0}^{t}[f_i^n(\tau)]^2, \quad (2)$$

where
f_i^n is the wavelet-transform component for t and t_0.

Wavelet packet analysis requires the choice of a basis function for the transform to accurately extract the energy characteristics of each frequency band. Commonly used discrete wavelets for acoustic emission signals and closely branched wavelet bases include Daubechies, Symlet, and Coiflet wavelets. However, it should be noted that the use of the Dmey wavelet allowed us to recover most of the spectral energy in all selected waveforms and localize most of the mechanical damage at the mesoscale.

Each fixed frequency band can be characterized by the relative energy of the acoustic signal in the volume of the laminated composite according to the formula

$$P_i^n = E_i^n(t)/\sum_{n=0}^{2^i}E_i^n(t). \quad (3)$$

The characteristics of each acoustic signal, including amplitude, duration, rise time, count, energy, centroid frequency, peak frequency and standard deviation, recorded during the three-point bending test were selected for correlation analysis and principal component analysis. The number of clusters *k* was calculated for characteristic ranges from 2 to 10. The calculations took into account two cluster validity methods to evaluate the best clustering performance. The first calculates the ratio of the distance within a cluster to the distance between clusters, and the second measures the amount of differentiation or separation of a cluster from other clusters.

Summary and conclusions. The acoustic field characteristics of composite material deformations show that the signals can be divided into four clusters. These clusters correspond to matrix cracking, delamination, fiber-matrix delamination, and fiber rupture, respectively. The clustering center analysis was performed based on the energy feature extraction methodology using wavelet packet decomposition. It was found that each damage mode corresponds to a frequency band with relatively high energy. The classification results postulated for the clustering method made it possible to determine the actual pattern of mechanical behavior in the bulk of the composite material. The k-means results indicate the existence of a slight difference in determining matrix cracking. The differences in the algorithms concern the signal amplitude for inter-laminar damage and a higher peak frequency for fiber rupture. The method proposed in this paper allows one to check the results of mechanical damage clustering well. In addition, the k-means algorithm performs better in recognizing the damage pattern of composites.

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