# IDENTIFICATION OF ACOUSTIC EMISSION USING CONTINUOUS WAVELET TRANSFORM

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Carbon fiber reinforced plastic has high stiffness, strength, and good resistance to corrosion and high temperatures. These properties make these composite systems a good candidate for numerous engineering applications. Unfortunately, long-term use of composites causes the occurrence of deformation zones. It should also be noted that damages can occur early in the manufacturing process and accumulate over the entire service life. Therefore, one of the primary tasks is to develop reliable and efficient online condition monitoring systems capable of detecting and classifying various damage sources. The technique of studying acoustic emission in the volume of a composite structure is considered one of the most suitable applications of condition monitoring, especially when it is associated with the study of the dynamics of deformation regions [1, 2]. The main method used for the purpose of identifying damage regions is based on the study of signal amplitudes [3]. Registration of acoustic waves is accompanied by their analysis in the time interval. The amplitude and energy are considered as the basic parameter describing the characteristic deformation modes. Each mode of mechanical deformation behavior is associated with a corresponding amplitude. The obtained results were not completely unambiguous due to the amplitude being dependent on the fiber orientation in the composite, the specimen geometry, and the location of the recording sensor. As a result, the amplitude of the acoustic waves is not captured as a characteristic feature for damage classification. Further development of the acoustic wave analysis technique is related to frequency-based analysis [4]. In particular, classical methods such as power spectrum analysis were used. An example is experiments investigating the damage dynamics of a unidirectional carbon/epoxy material under tensile testing. The results show that specific failure mechanisms can be identified and classified based on the peak frequency distribution. Based on numerous experimental studies, specific frequency bands associated with five failure modes (fiber pullout, fiber breakage, matrix cracking, delamination, and delamination) were identified. The frequencies caused by fiber pullout were in the range of 500-600 kHz, fiber failure was found to be in the range of 400-500 kHz. Frequencies between 300 and 200 kHz were obtained for fiber/matrix delamination, where delamination was given in the range between 50 and 150 kHz, and matrix cracking released frequencies between 50 and 100 kHz. The results of the above studies show that each failure mode is characterized by a specific frequency range. Frequency-based analysis shows less inconsistency and better potential for spatial localization of damage compared to amplitude-based analysis due to the non-stationary behavior of acoustic wave signals. The experimental results indicate that 98% of the acoustic wave energy in the volume of the composite material is concentrated at levels corresponding to the frequency ranges of 50–150 kHz, 150–250 kHz, and 250–310 kHz, respectively.

Wavelet transform contour maps revealed a correlation between local mechanical failure modes and the corresponding acoustic frequency ranges. In addition, tests on carbon fiber/epoxy resin plates with different geometries indicate that the obtained acoustic frequency responses are clearly different for different sources of mechanical strain. In particular, composite matrix cracking was accompanied by frequencies below 150 kHz, while fiber rupture was accompanied by frequencies above 400 kHz.

The main objective of this paper is to improve the classification method by extracting similarities with the characteristics of composite damage zones from acoustic wave analysis data. The continuous wavelet transform provides the corresponding time- and frequency-localized information that is analyzed simultaneously with high resolution in different frequency ranges. The continuous wavelet transform of a signal *f(t)* is defined as

$$\Psi(a,b) = a^{0.5} \int_{-\infty}^{\infty} f(t)\psi * \left[\frac{t-b}{a}\right] dt, \quad (1)$$

where the variable $a$ represents the scale and specifies the stretching and compression of the wavelet, while $b$ indicates the translation. The mother wavelet and its complex conjugate are defined as $\psi(t) \in L^2(R)$ and $\psi^*(t)$ respectively.

Principal component analysis is one of the most popular statistical analyses. It is commonly used to reduce the dimensionality of data sets. The analysis technique is based on an orthogonal linear transformation that generates new orthogonal and uncorrelated variables called principal components. These components are normalized eigenvectors of the covariance matrix of the original variable. The data vector is defined by the relation

$$X = TP^T = t_1 p_1^T + t_2 p_2^T + \cdots + t_m p_m^T = \sum_{i=1}^{m} t_i p_i^T, \quad (2)$$

where $p_i$ defines the eigenvector of the covariance matrix $X$.

Matrix $T$ is the principal components matrix; it provides information about the relationship between the samples. Matrix $P$ defines the loading matrix and contains information about the relationship between the variables. The statistical method of acoustic emission analysis takes into account the kernel density estimate for the set $S = \{x_1; x_2; \dots; x_N\}$ of the distribution density function $p(x)$. The density estimate at point $x$ is determined by the formula

$$\hat{p}_h(x) = (Nh)^{-1} \sum_{i=1}^{N} K_h[(x - x_i)/h], \quad (3)$$

where $K_h$ is a symmetric function integrating to unity and representing the kernel function; $h$ is a positive smoothing parameter that determines the bandwidth of the kernel.

Results of the acoustic emission analysis technique in the volume of the composite with a fixed waveform and frequency range extracted from the continuous wavelet transform, the quantitative and qualitative characteristics belonging to each signal are highlighted, so that differences between damage mechanisms are achieved. Numerical experiments show that each deformation mode is characterized by typical properties, namely, a bending mode, a stretching mode and a certain frequency range.

The signals related to composite delamination have the lowest frequencies, while the signals generated by fiber rupture have the highest frequencies. Acoustic emission signals with a frequency range of less than 120 kHz were attributed to delamination. Composite matrix cracking is accompanied by acoustic signals with frequencies from 100 to 150 kHz. Signals caused by fiber rupture were in the range of 350 to 500 kHz. Calculations show that the identified modes of change in the mechanical properties of the composite deformation regions are matrix cracking, fiber rupture, and fiber-matrix bond failure.

This technique combines continuous wavelet transform and statistical analysis to identify and classify acoustic emission data. For spatial identification of deformation areas, time domain parameters are not taken into account. Only wavelet coefficients are used as identifiers. Reducing the dimensionality of the wavelet coefficient matrix allows selecting characteristic features of mechanical damage. In addition, it is possible to limit the zone with high feature density by smoothing the two highest principal components of the matrix.

## References


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