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ANALYSIS OF ENERGY CRITERIA FOR WAVELET TRANSFORMS IN COMPOSITE STRUCTURES

АНАЛІЗ ЕНЕРГЕТИЧНИХ КРИТЕРІЇВ ВЕЙВЛЕТ-ПЕРЕТВОРЕНЬ У КОМПОЗИТНИХ СТРУКТУРАХ

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Abstract. *This work is devoted to the analysis of the effectiveness of wavelet transformations for the localization of deformations in composite materials obtained by the acoustic emission method. A detailed comparison of several discrete wavelet transformations was carried out according to energy and entropy criteria, as well as according to the η-parameter. The entropy and average energy criteria indicate the minimum effectiveness of Dmeyers-, Coiflet-, and Haar wavelets for detailing the deformation field. A similar exception from consideration must be made for the Dmeyers wavelet (db 24) according to the η-parameter. It was found that only the Daubechies wavelet meets all three criteria at the same time. The performed ranking of the density of the wavelet distribution within the threshold values indicated the preferred choice for the η-parameter.*

Key words: *wavelet analysis, composite materials, wavelet entropy, acoustic emission.*

Introduction.

The intensive development of technologies for the production and use of composites as multicomponent materials, the final properties of which are better than the properties of their components, is one of the characteristic features of recent times. In particular, carbon fiber-reinforced composite materials (CFRP) are used extensively in the aviation, automotive, and civil engineering industries. As a reason for the increased interest in composite materials of this type, one can point to such properties of the polymer matrix as high specific strength, high rigidity, and high corrosion resistance [1].

However, the presence of two or more dissimilar phases poses challenges in machining composite materials. The use of a multi-level operating mode of composites often causes deformation of the composite material. Such deformations include rupture, cracking and pulling out of fibers, crushing and cracking of the matrix, impaired adhesion, and delamination [2]. Delamination, in particular, leads to a decrease in strength and elastic modulus if the adhesion between the layers is not strong enough. It should be noted that these types of deformities are indistinguishable by visual inspection.

Technological processes for the manufacture and operation of carbon fiber structures require a constant volume of samples for the detection, assessment, and localization of possible damage. Acoustic emission of composite materials is one of the methods for such monitoring. Acoustic emission is a non-destructive technique that can provide in-situ monitoring of a structure using a network of distributed sensors and can be used to detect damage at a very early stage, long before the structure fails. When a structure is subjected to mechanical, thermal, or chemical stress, a stress field is created in the material. As a result of the accumulation of these damages, the material degrades. Acoustic emission can be considered as a short-term elastic release of energy in materials when microstructural changes occur.

Analysis of high-amplitude acoustic waves made it possible to study the process of destruction of multilayer composites [3]. It should be noted that the acoustic waves emanating from the processed material are usually non-stationary and contain overlapping transients. Therefore, to characterize these processes, an appropriate signal-processing method is required. Non-stationary signals require the use of Fourier series to process them. However, Fourier series processing of transient components, such as rapidly decaying frequency components, does not allow the extraction of characteristic features, and much of the useful information is averaged out and lost during signal conversion.

It should be noted that Fourier analysis can be considered as the basis for the use of continuous and discrete wavelet transforms in the study of deformation fields of composite structures. A large number of studies are devoted to expanding wavelet analysis for processing signals obtained from processing an array of data on the kinetics of deformations in a composite matrix. As an example, we can point to work [4], in which the relationship between the wavelet transform of acoustic signals and the failure modes of fiber-reinforced composites was studied in detail.

Multicomponent wavelet analysis.

In this work, the sentinel function was chosen as a quantitative characteristic of the energy of mechanical deformation E_d and acoustic emission E_a at displacement x

$$f(x) = \ln\left[E_d / E_a\right] \ . \tag{1}$$

Rényi entropy was chosen to describe the uncertainty of the probability amplitude distribution of the acoustic emission signal shape. An increase in Renyi entropy indicates the occurrence of an internal change in the composite material, which may be associated with the occurrence of damage.

$$H(S) = -\ln \sum_{i=1}^{n} P(S_i)^2 , \tag{2}$$

where $P(S_i)$ is the discrete probability distribution of the wave amplitude.

The relative energy of each subcomponent compared to the original signal can be related to the damage mode in the composite structure using the following relationship

$$E_{W,i} = \sum_{t'=t_1}^{t_2} \left[f_i^n(t')\right]^2 , \tag{3}$$

where the subcomponent n with energy $E_{W,i}$ is located in level i in time interval $t' \in (t_1, t_2)$.

The efficiency of the wavelet method was analyzed using experimental results on acoustic emission [4]. As a final stage, an analysis of the effectiveness of wavelet transforms was carried out to identify local damage to the composite material.

The influence of entropy on the stability of the acoustic signal was determined in this work using the following parameter

$$\eta = E_W / H \ . \tag{4}$$

In this work, the best wavelet was determined from a list of 24 wavelets using the previously stated criteria. The decomposition of an acoustic signal leads to the appearance of components containing the spectral energy of the signal, distributed in the time domain and located in a certain frequency band. These components correspond to damage types such as matrix cracking, delamination, matrix-fiber bond failure, fiber breakage, fiber pullout, and through-laminar crack growth.

The wavelet family included Haar- (Haar $k = 1$); Daubechies- (db k, $k = 2, \ldots, 11$); Symlet- (sym k, $k = 12, \ldots, 18$) and Coiflet- (coif k, $k = 19, \ldots, 23$) Dmeyers- (Dmey k = 24); wavelets. The results of determining the average entropy, average energy, as well as η-values are presented, respectively, in Figures 1, 2 and 3.

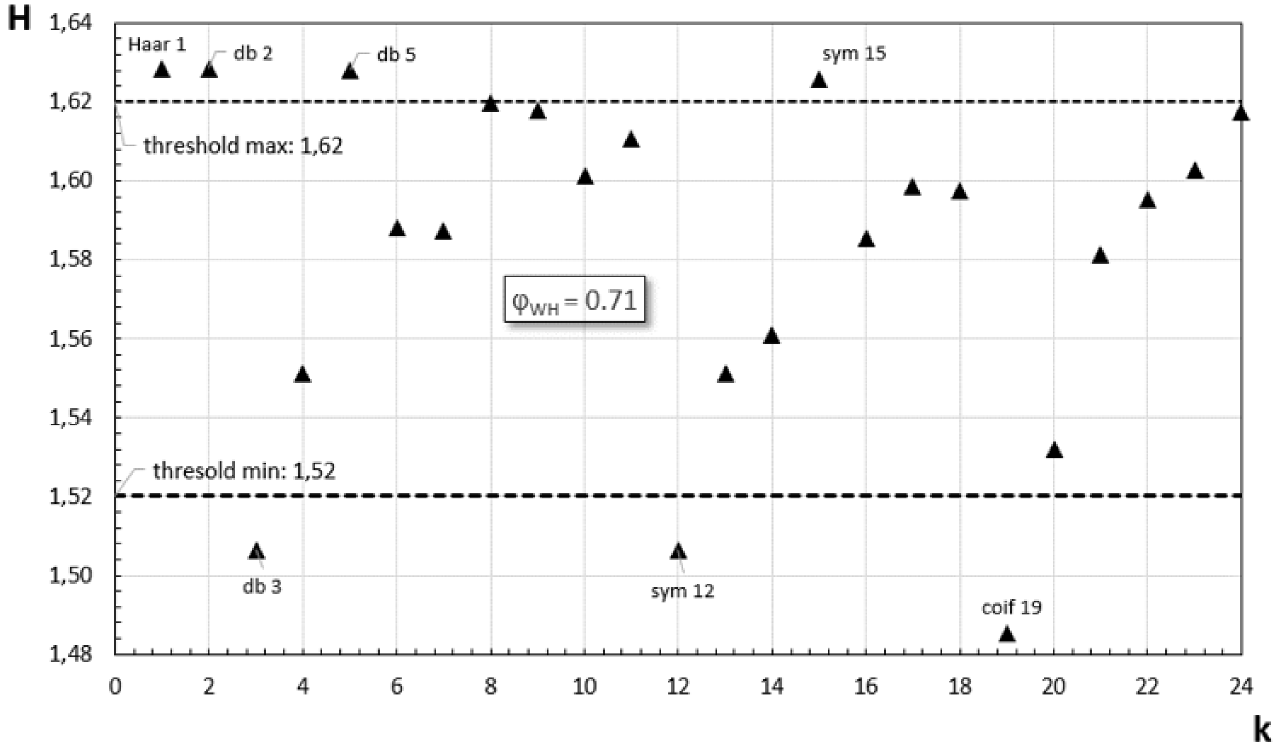

Figure 1 - H-distribution for wavelets according to the average entropy parameter.

The diagrams display the results of assessing the critical values of the threshold values for selecting the maximum and minimum parameters “threshold max” and “threshold min”. In addition, for a series of wavelets, the distribution density of wavelets in the min-max band was estimated using the formula

$$\varphi_{W,k} = N_{W,k}^{-1}(N_{W,k} - \Sigma_{\min,\max}),\; k = H, E_W, \eta, \qquad (5)$$

where N_W is the total number of wavelets in the series, $\Sigma_{min,\ max}$ is the number of wavelets, whose corresponding parameters are outside the threshold values.

The H-distribution is characterized by a sufficiently large number of wavelets, the average entropy of which is outside the threshold values.

In particular, the following wavelets are located above the maximum threshold: Haar- and Daubechies- (subseries db k, k = 2, 5, 15). Three wavelets, namely: Daubechies- (db 3), Symlet- (sym 12), and Coiflet- (coif 19) have an average entropy value less than the minimum threshold value (= 1.52). It is quite natural that preference in terms of the min-max parameter for entropy should be given to Daubechies wavelets with indices k = 2, 3 and 5. Accordingly, Haar- and Coiflet wavelets should be excluded from further analysis in terms of the entropy parameter.

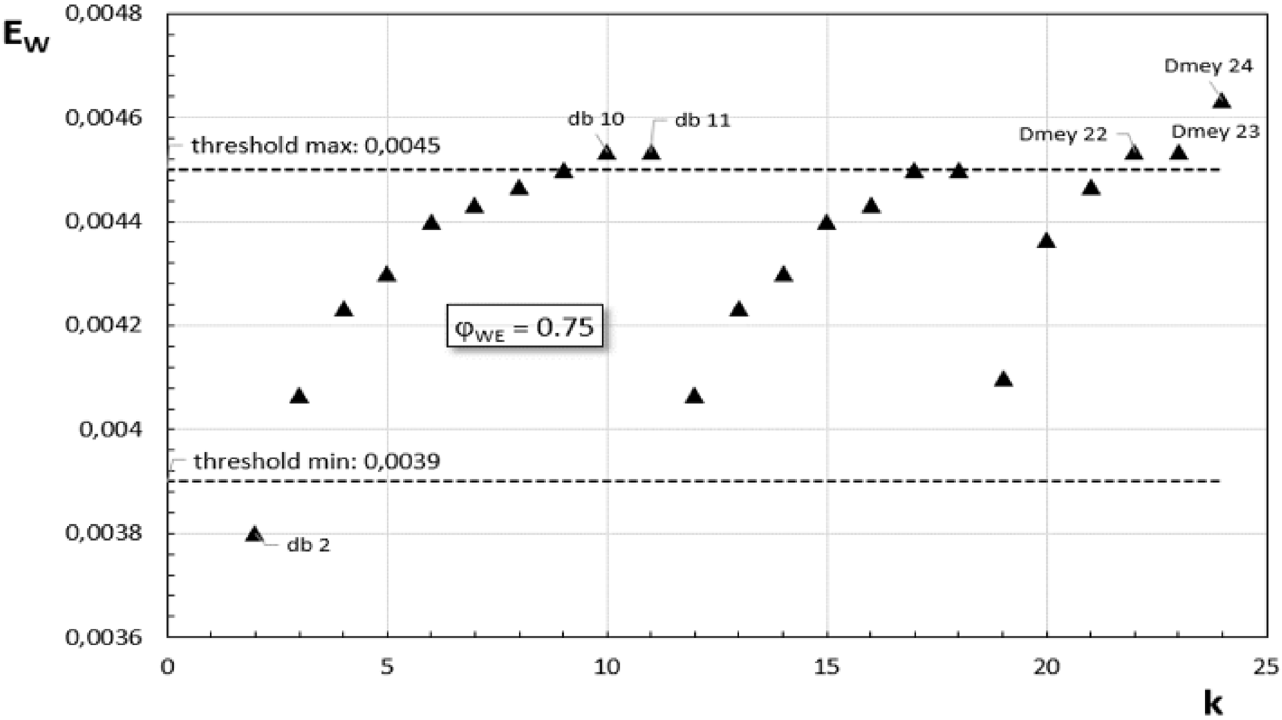

Figure 2 - E-distribution for wavelets according to the average energy parameter.

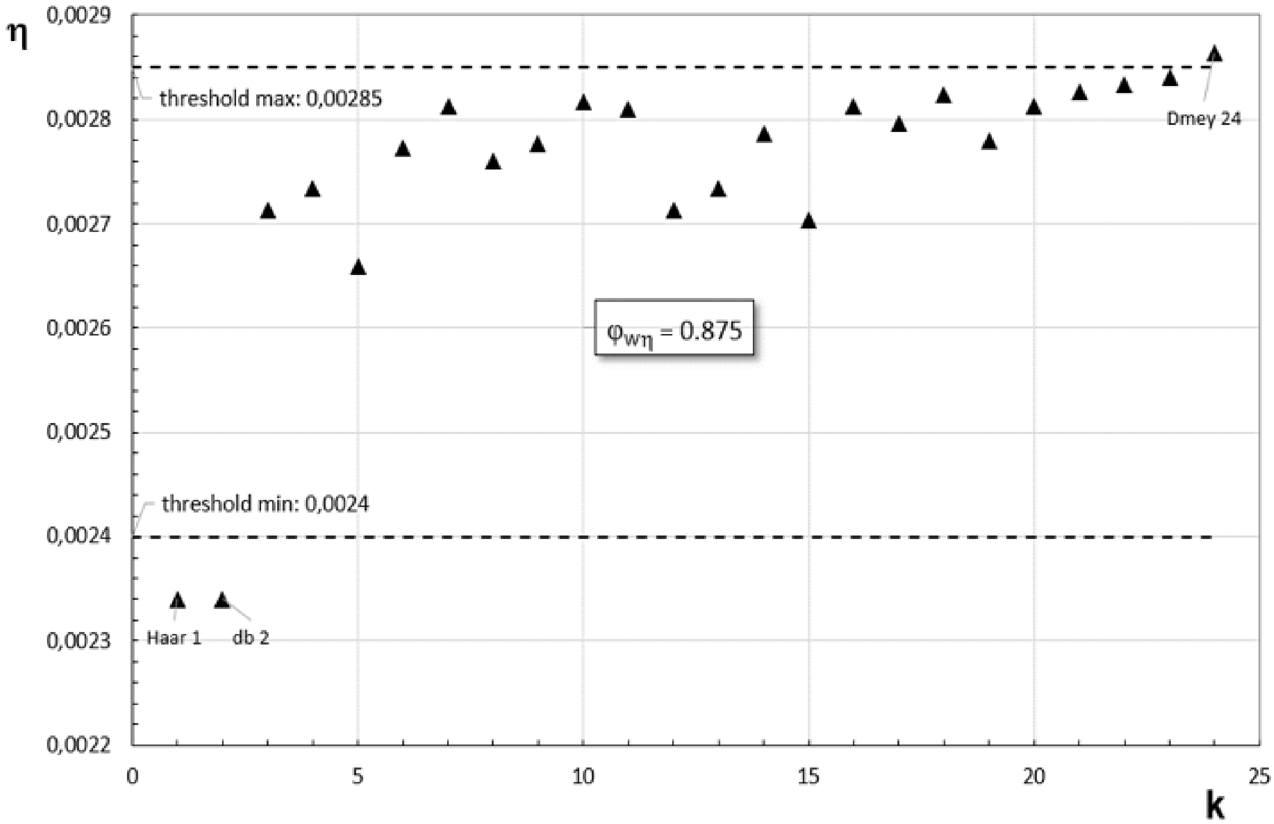

Figure 3 - η-distribution for wavelets.

The average energy distribution is characterized by a maximum difference $\Sigma_{max,\ min}$ = 4. Exceeding the maximum threshold for average energy is typical for wavelets: Daubechies- (db *k* subseries, *k* = 10, 11) and Dmeyers- (Dmey *k* subseries, *k* = 22 - 24). Below the minimum threshold for average energy there is only one wavelet:

Daubechies- (db 2). Preference for the min-max parameter for the average energy should be given to the Daubechies wavelet with index k = 2. Accordingly, Dmeyers wavelets with indices k = 22, 23 and 24 should be excluded from further analysis for the average energy parameter.

In turn, only one wavelet, namely, Dmeyers- (db 24), exceeds the maximum threshold in the η-parameter. Wavelets: Haar 1 and Daubechies- (db 2) are located below the minimum threshold in the η-parameter. The absence of repeating wavelets from one, fixed series makes it difficult to select wavelets based on the min-max parameter for the η-value.

Conclusions. As a result of the analysis, recommendations for choosing the optimal wavelet having average energy, average entropy, and η-parameter, that satisfy the min-max parameter should be pointed to Daubechies-wavelet (db 2). Ranking the distribution density of wavelets within threshold values for average energy and entropy, as well as the η-parameter, leads to the following chain:
$\varphi_{W\eta}$ (= 0.875) > φ_{WE} (= 0.75) > φ_{WH} (= 0.71).

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Анотація. *Представлена робота присвячена аналізу ефективності вейвлет-перетворень для локалізації деформацій у композитних матеріалах, отриманих методом акустичної емісії. Проведено детальне зіставлення низки дискретних вейвлет-перетворень за енергетичними та ентропійними критеріями, а також за η-параметром. Критерії ентропії та середньої енергії вказують на мінімальну ефективність Dmeyers-, Coiflet- та Haar-вейвлетів, для деталізації деформаційного поля. Аналогічний виняток із розгляду необхідно виконати і для Dmeyers-вейвлета (db 24) по η-параметру. Отримано, що лише Daubechies-вейвлет одночасно відповідає всім трьом критеріям. Виконане ранжування щільності розподілу вейвлетів в межах порогових значень вказало на переважний вибір для η-параметра.*

Ключові слова: *вейвлет-аналіз, композиційні матеріали, вейвлет-ентропія, акустична емісія.*

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