KAPITEL 10 / CHAPTER 10 [10]
WAVELET DECOMPOSITION FEATURES OF ACOUSTIC EMISSION IN COMPOSITE MATERIALS

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Introduction.

The widespread use of composite materials in various fields of industry is due to the peculiarities of their structure and mechanical properties. However, the operating conditions of these materials, associated in particular with the influence of humidity and temperature, lead to the appearance of intra-volume and surface deformations. The heterogeneous nature of composite materials, together with their anisotropic characteristics and the relative brittleness of the matrix/fibers, results in a complex array of failure modes when loaded under static and/or fatigue conditions. These modes include transverse matrix cracking, fiber breakage, splitting (matrix cracking along the fiber) and delamination. Therefore, optimal use of composite materials requires constant monitoring of their structure.

The non-destructive acoustic emission method makes it possible to monitor the condition of structures. Acoustic emission is one of the non-destructive methods capable of detecting and monitoring in real time the development of damage and destruction of composite materials. The acoustic emission technique makes it possible to obtain released energy in the form of transient elastic waves due to the formation and development of damage in a mechanically loaded sample. The advantage of this non-invasive method is that it only works in passive mode using sensors attached to the surface of materials and structures. Advanced acoustic emission analysis typically uses additional parameters such as amplitude distribution, RMS values, and waveform studies.

Traditional spectral analysis is often used to analyze acoustic emission signals in composite materials. However, for many problems, wavelet analysis is still preferable, in which the signal is divided into a series of orthogonal basis functions of finite length.

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The structure of a wavelet signal, such as, for example, a signal about crack propagation, can be analyzed by its local features. Wavelet functions can be thought of as a set of basic functions that can separate a signal by time and frequency, so the wavelet transform can detect many unknown aspects of the response signal.

In recent years, many studies of the deformation field in composites have been carried out using wavelet analysis of the spectrum of acoustic emission signals. In particular, Khamedi et al. [1] used the wavelet transform to identify the failure mechanisms of unidirectional carbon-epoxy composites. For this purpose, carbon-epoxy composites were tensile tested under two different loading conditions, which were applied along and perpendicular to the fiber directions, respectively. The authors discovered and quantitatively described both two frequency ranges of acoustic emission associated with the main mechanisms of interfacial failure, as well as the acoustic wave features for additional mechanisms of matrix cracking and fiber breakage.

Kamala et al. [2] was used wavelet transform decomposition to gather time-frequency-based information from the acoustic emission signals generating during fatigue loading of unidirectional carbon fiber reinforced composite. It was determined that most of the acoustic energy (95%) was localized in levels corresponding to three fixed central frequencies. Results indicate friction-related emissions are associated with amplitude levels and have a frequency range of 17% of its maximum value. There are indications that matrix related emissions are of high frequency and high acoustic energy.

Satour et al. [3] proposed new descriptors related to the continuous wavelet transform, where the acoustic signals are decomposed and calculated using the corresponding wavelet coefficients. In addition, for each matrix deformation mechanism, a specific vector composed of wave coefficients was established. This vector represents the wavelet coefficients calculated using the continuous wavelet transform and the entropy criterion. The authors proposed new possibilities for the classification process of unidirectional composites, namely, the center of each class was calculated using the k-means algorithm.

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This work is divided into two parts. The first part highlights the results of the analysis of wavelet decomposition of acoustic signals in laminar composites. A detailed study of the dynamics of acoustic wave propagation in composites of different types of symmetries is presented in the second part.

10.1. Wavelet decomposition of acoustic signals.

In this work, the effectiveness of using wavelet transforms for acoustic signals in laminar composites was studied using the example of Dmey-, coif 5- and coif 4-wavelets. Acoustic signals can be decomposed into 8 wavelet components WF_i, $i = 1, 2, ..., 8$. For each transformation, the results of processing the responses of composite structures to acoustic emission signals were used [4]. Wavelet components were analyzed separately for eight frequency ranges in the range $F_W \in (0 \div 5)\cdot 10^5$ Hz. The width of each sub-band was $\Delta F_W = 6.25\cdot 10^4$ Hz.

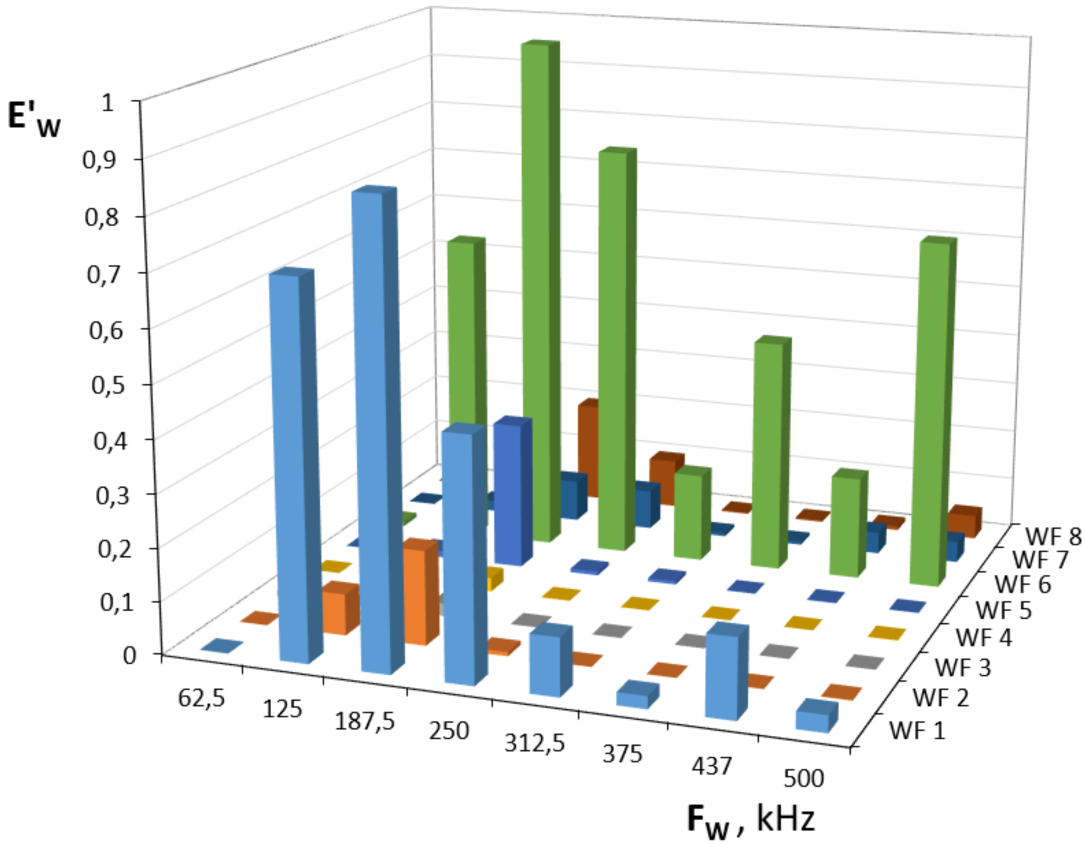

Figure 1 - Spectral distribution $E'_W = f(F_W)$ for Dmey-wavelet.

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The analysis showed that the dominant frequencies differ from each other for each signal. The reason for this difference may be that each of these dominant frequency bands represents different types of damage from which acoustic signals originate.

The spectral distributions of dimensionless relative energy E'_W were studied for wavelets of three characteristic shapes: Dmey-, coif 4- and coif 5-. The results are presented in Figures 1, 2 and 3.

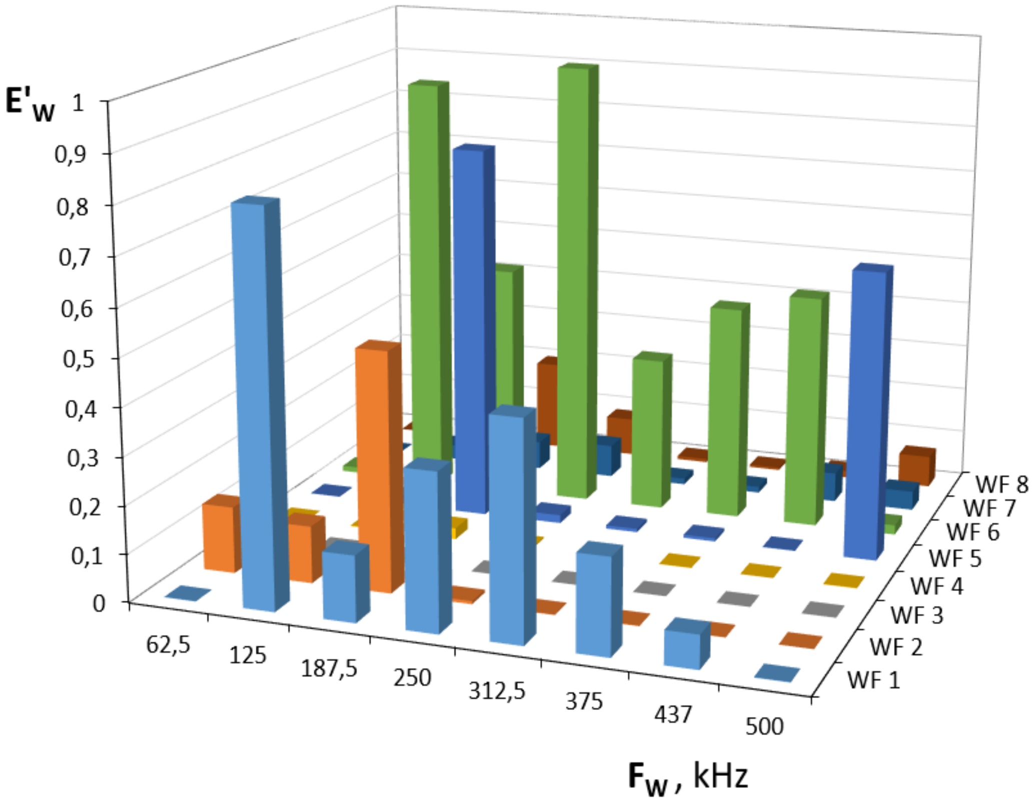

Figure 2 - Spectral distribution $E'_W = f(F_W)$ for coif 4-wavelet

The Dmey-wavelet presented the greatest efficiency in restoring spectral energy in all selected signal forms. However, the coif 5-wavelet also recovered most of the spectral energy, although it is not present among all the selected 8 wavelet decomposition modes. Comparing the spectral energy of a large number of signals leads to the conclusion that a significantly larger number of signals that have recovered most of the spectral energy arise when they are decomposed using the Dmey-wavelet. These factors are the reason why the Dmey-wavelet is selected as the best wavelet for acoustic signal processing in this study.

The resulting spectral distribution of Dmey- and coif- wavelets is characterized by the predominant contribution of the k-components WF (k = 1, 6).

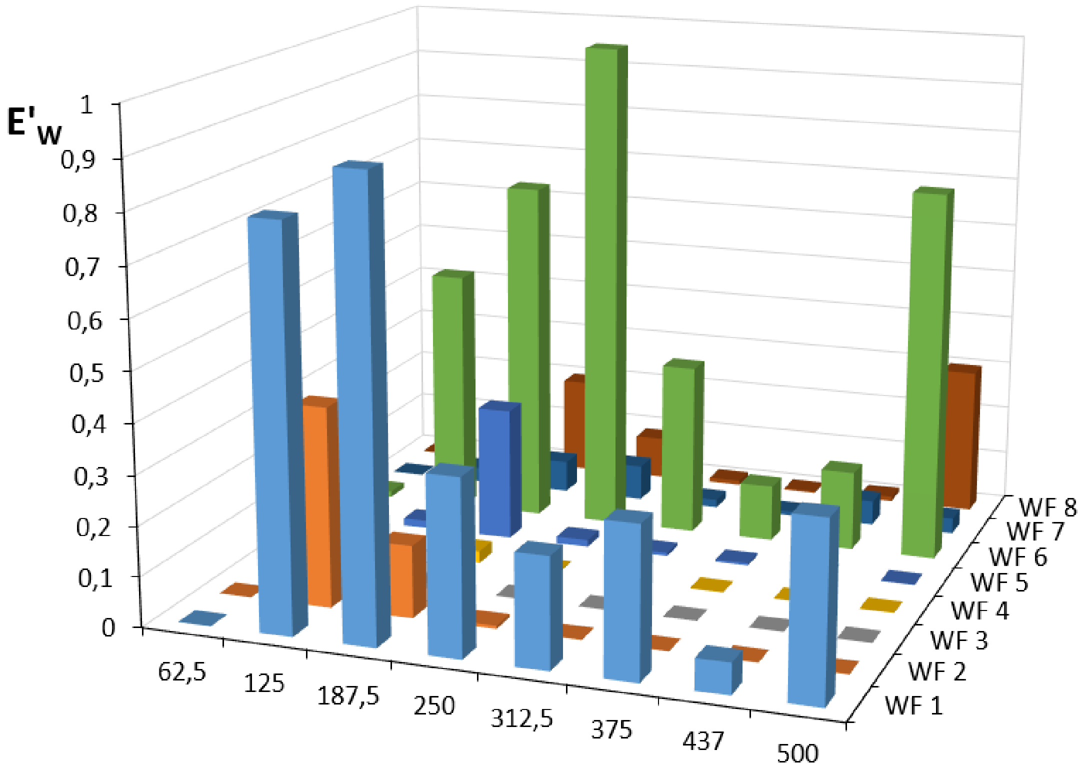

Figure 3 - Spectral distribution $E'_W = f(F_W)$ for coif 5-wavelet.

Based on these facts, a separate analysis of the frequency dependence in matrix form was carried out for WF_k

$$E'^{(k)}_W(x) = \alpha^{(i,k)} F^{(i)}_W, \quad i = 0,1,\dots,5; \quad k = 1,6. \tag{1}$$

The $\alpha^{(i,k)}$ coefficients are given in Table 1.

Spectral dependency analysis suggests that wavelet analysis of acoustic emission response signals has the potential to reveal the damage process of composite structures because it can differentiate acoustic signals based on frequency and time domain characteristics. However, the waveforms are characteristic of loading stages, which, of course, is a factor limiting the use of wavelet analysis for detecting damage in composite structures. Isolation of the dominant frequency band using the wavelet transform using the best wavelet still makes it possible to identify the process of destruction of the internal structure of two-component composites, the inclusions in which differ in size by no more than an order of magnitude.

Table 1 - Binomial coefficients for relative energy.

$(i$, k)	Dmey-wavelt					
$(i$, 1)	$-3.2\cdot10^{-1}$	$-1.2\cdot10^{-2}$	$4\cdot10^{-4}$	$-3\cdot10^{-6}$	$6\cdot10^{-9}$	$-5\cdot10^{-12}$
$(i$, 6)	3.32	$-2.7\cdot10^{-1}$	$4.9\cdot10^{-3}$	$-3\cdot10^{-5}$	$6\cdot10^{-8}$	$-5\cdot10^{-11}$
	coif 4-wavelet					
$(i$, 1)	$-4\cdot10^{-1}$	$1.1\cdot10^{-1}$	$-9\cdot10^{-4}$	$3\cdot10^{-6}$	$-6\cdot10^{-9}$	$4\cdot10^{-12}$
$(i$, 6)	-7.3	$4.2\cdot10^{-2}$	$1.9\cdot10^{-3}$	$-2\cdot10^{-5}$	$4\cdot10^{-8}$	$-3\cdot10^{-11}$
	coif 5-wavelet					
$(i$, 1)	-1.5	$2.2\cdot10^{-2}$	$9\cdot10^{-5}$	$-1\cdot10^{-6}$	$4\cdot10^{-9}$	$-3\cdot10^{-12}$
$(i$, 6)	-6.7	$2.9\cdot10^{-2}$	$2\cdot10^{-3}$	$-2\cdot10^{-5}$	$4\cdot10^{-8}$	$-5\cdot10^{-11}$

10.2. Dynamics of acoustic wave propagation in composites.

The necessary condition for describing the dynamics of acoustic propagation is a nonstationary representation of the deformation field of a two-component composite structure. Let us consider the propagation of a pulse load acoustic wave, which simulate the peak change in the stiffness of a composite material in the form of a rectangular beam. The type of load is a narrow peak band sinusoidal base

$$f(t) = N_P B \cdot \Delta H(t) \cdot \left[1 - \cos\left(2\pi f_0 t / N_P\right)\right] \sin\left(2\pi f_0 t\right), \quad (2)$$

where $H(t)$ is the unit step function, f_0 is the constant frequency, $N_P = \text{const}_1$, $B = \text{const}_2$.

The narrowband pulsed load was used to demonstrate the non-dispersive characteristics of this type of load. The definition of narrow and wide bandwidth refers to the frequency spectrum of the signals and depends on the ratio of the bandwidth to the center frequency.

It makes sense to use the wavelet approach to find the shortest arrival time for various frequency components of the signal. The continuous wavelet transform *WT* of a function is defined by the formula

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$$WT_f(a,b) = a^{-1/2}\int_{-\infty}^{\infty} f(t)\psi^*((t-b)/a)dt, \quad a>0. \qquad (3)$$

The parameter *a* represents the scale variable in the wavelet transform, which is similar to the frequency variable in the Fourier transform. The value *b* represents the shift parameter.

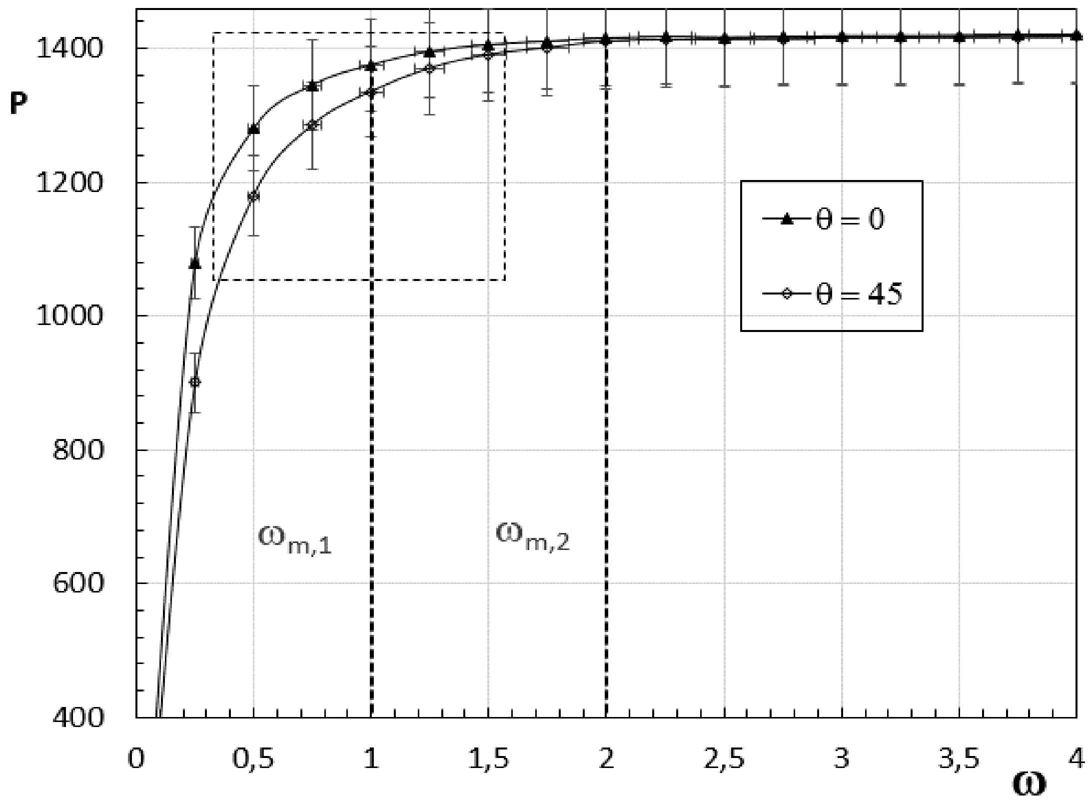

Figure 4 - Phase velocity of the first acoustic mode in composite A.

Knowing the dependence of the circular frequency ω on the projections k_x and k_y of the wave vector of acoustic emission onto the Cartesian axes, the phase and group velocities are determined from the relations

$$\upsilon'_P = \omega / k, \quad \upsilon'_G = d\omega / dk \qquad (4)$$

or in dimensionless version phase velocity

$$\upsilon_P = \left(\omega^2 \rho / k^2 E_1\right)^{0.5}. \qquad (5)$$

The first three wavelet-modes obtained in the calculations are acoustic modes, which can also propagate at lower frequencies. The lowest of them corresponds to the bending mode, the second to the planar shear of laminar type composite, and the third

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to the tensile wavelet-mode of composite deformation field. The frequency at which the other two modes, known as optical modes, begin to propagate is called the cutoff frequency, and these modes are related to wavelet-transforms ψ_x and ψ_y, which are the rotations of the cross section.

In this study, the first acoustic mode, which is the lateral deflection, was analyzed and its group and phase velocities are shown in Figures 4 and 5 for composite plates.

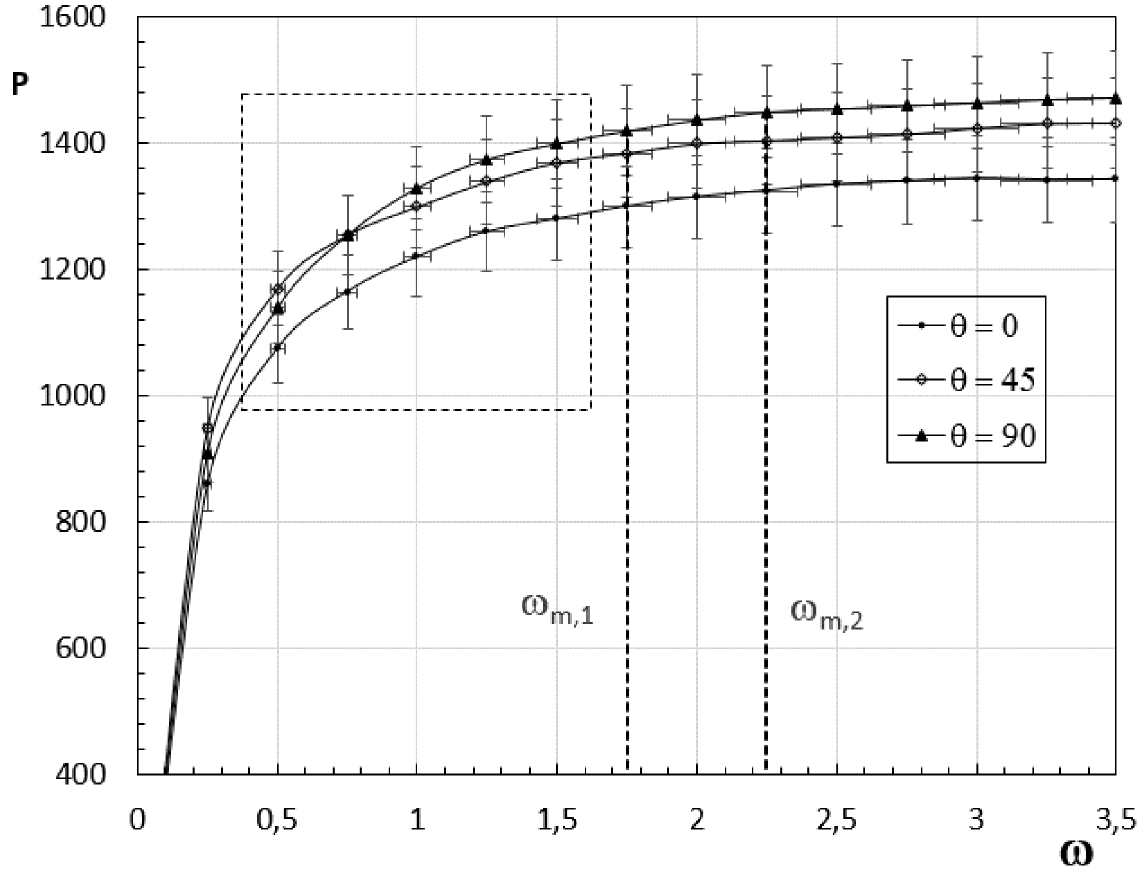

Figure 5 - Phase velocity of the first acoustic mode in composite B.

For the spectral distribution of the phase velocity of acoustic waves, it is necessary to analyze the deformation fields of composite materials with two different types of symmetry (the presence, respectively, of two and three axes of symmetry). The composite plate with type *A* has three axes of symmetry around $\theta = 0^0, 45^0, 90^0$, and composite plate with type *B* has two axes of symmetry around $\theta = 0^0, 90^0$.

The phase velocity for a composite of the first type ceases to change significantly at $\omega_S = 1.2 \cdot 10^6$. The phase velocities of the second type composite sample practically reach saturation at $\omega_S = 1.5 \cdot 10^6$. The numerical value of the saturation frequency for

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group velocity increases compared to the case of phase velocity and is $\omega_S = 3.2\cdot10^6$ for the first sample and $\omega_S = 4.3\cdot10^6$ for the second sample.

The maximum change in the phase velocity of acoustic waves occurs in the interval of cyclic frequencies $\Delta\omega_A \in (0.4 - 1.6)$ for a type A composite. A composite with a type B structure with three axes of symmetry forms a phase velocity with a maximum change in the range $\Delta\omega_B \in (0.3 - 1.65)$. It can be argued that the presence of three axes of symmetry in a composite material slightly increases the range of frequencies for which the maximum change in phase velocity is observed.

The intervals for reaching the threshold value for the dispersion dependences of the phase velocity are $\omega_{m,2}$ - $\omega_{m,1} = 1$ and $\omega_{m,2}$ - $\omega_{m,1} = 0.5$ for composite materials of type A and B, respectively.

The components of the wave vector satisfy the equation

$$\theta = \arctan\left(k_y / k_x\right), \tag{6}$$

where θ is the wave propagation angle.

The similarity between the acoustic signal shape in the volume of the composite material and the corresponding wavelet function can be assessed using the inner product of this function and the recorded signal. When the parameters a and b are the values to which the waveform and wavelet function best fit, the calculations yield the maximum value of the wavelet coefficient.

The time shift that maximizes the inner product of the wavelet function for scale a and the acoustic signal is the arrival time Δt of the acoustic wave, which is related to the frequency and scale of the composite material sample

$$\omega = \omega_0 / a\Delta t, \quad f = f_0 / a\Delta t. \tag{7}$$

Estimating the location of the applied load and the associated local deformation requires using the time of arrival of the acoustic wave and the dominant frequency content of the signal. These quantities, specified using the presented wavelet approach, should form a system of nonlinear equations. For the case of a composite laminated composite plate, group and phase velocities values are used for the dispersion relations.

The position of the composite material sample and the fixation of the registration points of the arrival of the acoustic wave are determined by the triple of angles θ_1, θ_2 and θ_3, for which a system of nonlinear dispersion relations can be written. The solution of this system allows us to determine not only the quantities, but also the corresponding Cartesian coordinates of the corresponding local deformation for each frequency.

Summary and conclusions.

Have been considered the results of relative energy spectral distributions. This results indicate the preferable use of the Dmey-wavelet for the decomposition of acoustic waves. We received the generalized binomial representation for the corresponding wavelet transform. A detailed analysis of the spectral dependencies for the phase velocities of composite materials with different types of symmetry was performed. It was found that an increase in the number of symmetry axes leads to a slight increase in the interval for the most rapid change in phase velocity of acoustic waves.