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Energy Spectrum of Acoustic Emission Signals in Coupled Continuous Media

V.V. Marasanov[1,*], A.V. Sharko[2,†], A.A. Sharko[1]

[1] *Kherson National Technical University, 24, Berislav Shosse St., 73008 Kherson, Ukraine*
[2] *Kherson State Maritime Academy, 20, Ushakov Ave., 73009 Kherson, Ukraine*

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The regularities for the existence of elastic energy of initiating AE signals operators establishment is one of the unsolved problems of nanostructure modeling and the physics of nanosystems. The propagation of acoustic emission signals with the coupling of two continuous media is considered. The main variables in the equations of motion for particles are the force that determines the occurrence of acoustic emission and the displacement of particles of the medium, which determines the elastic wave propagation. A methodological basis for determining the energy spectrum of acoustic emission signals in coupled media using the Green function and Fourier transforms is presented. The conditions for the existence of an elastic energy operator for initiating acoustic emission signals are substantiated. The first basic condition that the elastic energy operator must satisfy is the invariance of the particles of the material structure relative to the translation. The second main condition for the existence of the elastic energy operator is its hermiticity The third basic condition, which the elastic energy operator must satisfy, is its homogeneity, which is based in its invariance with respect to the shift. The unequivocal correspondence between the characteristics of the discrete structure of materials and parameters of propagation of AE signals in conjugate media is established. Based on a comparison of the calculated characteristic numbers of the spectrum and the load diagram for discontinuous tests, it was shown that the energy spectrum of acoustic emission signals in coupled continuous media is completely determined by the material power constants and the forces initiating the appearance of acoustic emission signals. Presented energy spectrum of acoustic emission signals in conjugated continuous media models allows to associate them with the formation of metal crystal lattice defects and can be used to predict the stage of material destruction. The experimental verification of the main theoretical models of the energy spectrum of AE signals in a medium with a developing defect, at different stages of the load diagram, showed their consistency and satisfactory agreement in the basic details of the energy spectrum structure.

Keywords: Acoustic emission, Signals, Spectrum, Coupled continuous media, Eigenvalues, Eigenfunctions, Second-kind Fredholm equation, Fourier transform.

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1. INTRODUCTION

Study of the energy spectrum of signals of nanosized objects is explained by the importance of solving questions about the propagation of vibrations characteristics preceding the destruction of materials. In recent years, new models of continuum mechanics have been intensively developed. They describe composite and statistically heterogeneous environments of new structural materials, as well as the theory of defects, their occurrence and distribution under the influence of external disturbances [1-3]. The method of acoustic emission (AE), based on the registration of stress waves resulting from changes and destruction of the various materials structures, is currently the most promising means of monitoring of important objects, which obtain information on the dynamics of the processes taking place in real time. The connection between the process of defect formation and the presence of AE signals allows us to determine the degree of efficiency of structure material under changing external operating conditions [4-6]. Among the technical applications of AE control, coupled media in the form of protective coatings on metal and polymer base are of the greatest interest.

Theoretical studies of the occurrence of AE signals with changes in the material structure are developed in two main areas: the development of discrete models [7, 8] and models of the elastic continuum [9, 10]. Continuous models reflect free damped vibrations in unlimited medium, discrete ones are forced vibrations when scattered over local inhomogeneities and the propagation boundaries of AE signals. The periodicity of the crystal lattice, its structure, and the constitution of atoms determine the features of the energy spectra. With a known force field, by solving the equations of motion, it is possible to obtain information on changes in the material structure that cannot be directly measured [11, 12]. The regularities for the existence of elastic energy of initiating AE signals operators establishment is one of the unsolved problems of nanostructure modeling and the physics of nanosystems.

2. ESTABLISHMENT OF INITIAL CONDITIONS

The simplest model of the atomic interaction in a homogeneous medium can be represented as a system of point masses connected by springs with deflection rate Ψ_n (see Fig. 1).

The interactions of the nearest and next neighbors are shown on the basis of symmetry conditions. These interactions, indicated on the scheme by periodically

* volodymyr.marasanov@mail.ru
† mvsharko@gmail.com

repeating contours, should be identical that is confirmed by the results of previous theoretical studies in [9, 13].

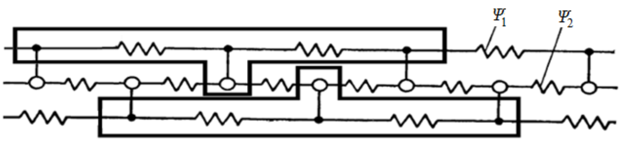

Fig.1 – The scheme of atomic interaction in a homogeneous medium

The figure, bounding the region of interaction of atoms, has a rotary symmetry, i.e. turns into itself at all turns. Symmetry, in addition to the ratio of proportions, determines the type of model parts consistency.

The equation of motion of homogeneous medium particles under the influence of external forces initiating the appearance of AE signals is obtained from the condition of homogeneity of the medium and stationarity of the action [9]:

$$m\ddot{u}(n,t)+\sum_{n'}\Phi(n,n')u(n',t)=q(n,t)\,, \qquad (1)$$

where $u(n, t)$ is the displacement of atoms from the equilibrium positions, $q(n, t)$ is the external forces acting on the chain.

Force constants $\Phi(n, n')$, which determine the properties of the model, are the parameters of elastic bonds between atoms [13]. From the symmetry condition it follows that $\Phi(n, n') = \Phi(n', n)$.

From the condition of homogeneity of the chain, it follows that for any n, n', n'': $\Phi(n+n'', n'+n'') = \Phi(n, n')$.

Using Fourier transforms in (x, t) and (x, ω), the representations of the equation of particle motion can be written as:

$$\rho(x)\ddot{u}(x,t)+\int\Phi(x-x')u(x',t)dx'=q(x,t), \qquad (2)$$

$$-\rho\omega^2u(x,\omega)+\int\Phi(x-x')u(x',\omega)dx'=q(x,\omega)\,, \qquad (3)$$

where ρ is the density of the medium material.

The presence of internal bonds between the particles of the microstructure and their destruction caused by the formation of defects should be manifested in a change of the oscillatory properties of the coupled media.

3. DISCUSSION OF RESULTS

A model of a two-layer continuous medium is proposed in the form of a chain of linear atoms connected by elastic bonds with a single point developing defect (see Fig. 2).

Dashed lines denote the breaking of atomic bonds caused by the destruction of the structure, leading to the formation of defects and the appearance of AE signals.

When two continuous media are coupled in each media, one can distinguish boundary regions S and S* in which the AE signals propagate. They have different sizes depending on the mechanical properties of the media materials.

The operator of elastic bonds in the coupling of two media Ψ is the sum of the interaction operators of the atoms of the corresponding media $\Psi=\Psi_V+\Psi_{V*}+\Psi_{VV*}$, where $\Psi_V\overset{def}{=}V\Psi V$, $\Psi_{V^*}\overset{def}{=}V^*\Psi V^*$, $\Psi_{VV*}\overset{def}{=}V\Psi V^*+V^*\Psi V$.

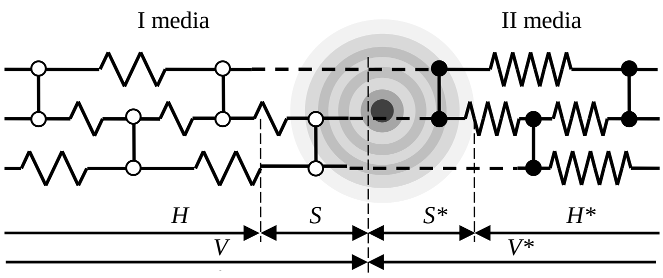

Fig. 2 – Scheme of occurrence of AE signals in coupled media: ○ – atoms of the first media, ● – atoms of the second media

Symbol $\underline{def}$ means "equal by definition".

The first main task of the propagation of AE signals in coupled continuous media is their consideration in the boundary areas given by the forces q_S and $q_{S'}$.

The equations of particle motion in the boundary regions S and S^* in operator form are

$$-\omega^2\rho_S u_S+S\Phi u=q_S,\;\; -\omega^2\rho_{S*}u_{S*}+S*\Phi u=q_{S*}\,.$$

Since the occurrence of the AE source is possible with equal probability in both media, in the following we omit the index * and, for V area, the equation of motion for particles has the form:

$$-\omega^2\rho u_V+\Phi_V u_V=q_V\,.$$

The structure of the energy spectrum of AE signals can be determined using the second type Fredholm equation [14]:

$$y(x)=\lambda\int_a^b k(x,t)y(t)dt+f(x)\,, \qquad (4)$$

where $k(x, t)$ is the kernel of integral equation, λ is a numerical factor (characteristic number), a, b are limits of integration (boundary conditions), $f(x)$ is the free term which is a continuous function on a segment $a \le x \le b$, $y(x)$ is an unknown definable function.

The task is to ensure that for a given continuous function of the kernel $k(x, t)$ and function $y(t)$, which characterize the received AE signal, to find function $y(x)$, which characterizes initiated AE signal from the precursor of destruction. The collection of characteristic numbers λ defines a range of functions $y(x)$.

We assume that the kernel $k(x(t))$ is symmetric, continuous and bounded, and the free term $f(x)$ is a continuous function when $a_x \le x \le b_x$, $a_t \le t \le b_t$ (Fig. 3).

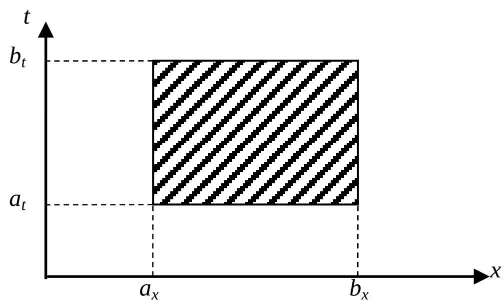

Fig. 3 – Spatial and temporal localization of the transmission of AE signals

The boundary problem of determining the energy spectrum of AE signals in coupled media is finding solutions to differential equations that satisfy the boundary conditions of two media S and S^*.

The kernel of the Fredholm equation of the second type can be determined through the differential operator of the equation of the medium particle motion.

The Fredholm equation of the second type allows its reduction to a boundary value problem, if it is possible to choose the Green function, which determines the kernel of a given integral equation.

As to the boundary conditions of the problem of determining the energy spectrum of AE signals in coupled continuous media, the function $G(x, \omega)$ describes the vibration of the medium caused by the force located at the origin of coordinates and represents the displacement field created by the unit force acting on one atom of the chain. If the Green function is found, then the solution of the boundary problem takes the form

$$y(x) = \int_a^b G(x,\omega) f(\omega) d\omega .$$

We represent it in the form of a sum of total and particular solutions. To find the particular solution, it is necessary that the Green function $G(x, \omega)$ satisfies the equation:

$$-\rho\omega^2 G(x,\omega) + \int \Phi(x-x')G(x',\omega)dx' = \delta(x) ,$$

where $\delta(x)$ is the Dirac function.

Considering the x coordinate as a parameter, the transition from the discrete argument n to the quasi-continuous arguments x and k can be made. The kernels of the presentation forms are related by

$$q(n) = \sum_{n'} \Phi(n,n')u(n'), \qquad q(x) = \int \Phi(x,x')u(x')dx',$$
$$q(k) = \int \Phi(k,k')u(k')dk',$$

Functions $q(n)$, $q(x)$, $q(k)$ are kernels of the functional $\langle q \mid u\rangle$ in n, x and k representations. They can be interpreted as the scalar product of functions q and u:

$$\langle q|u\rangle = \langle \overline{u\,|\,q} \rangle .$$

They are Hermitian-conjugate, which corresponds to the third condition for the existence of an elastic energy operator. Hermitian form Φ^+ in n, x, and k representations has the form:

$$\Phi^+(n,n') = \overline{\Phi(n',n)}, \qquad \Phi^+(x,x') = \overline{\Phi(x',x)},$$
$$\Phi^+(k,k') = \overline{\Phi(k',k)}.$$

In this case

$$G(x,\omega) = \frac{1}{2\pi\rho}\int \frac{e^{ixk}}{\omega^2(k)-\omega^2}dk .$$

Having constructed the Green function, $G(x, \omega)$, a particular solution of the equation can be expressed through it (3)

$$u(x,\omega) = \int G(x-x',\omega)q(x',\omega)dx' .$$

The general solution of equation (3) is:

$$u(x,\omega) = \sum_{m=0}^{\infty}\left(a_m e^{ik_m(\omega)x} + \beta_m e^{-ik_m(\omega)x}\right),$$

where a_m and β_m are arbitrary constants.

It is a superposition of solutions corresponding to each root $k_m(\omega)$. Its solution is complicated by the fulfillment of the numbering conditions of complex integrand roots. An alternative is the transition to the Green function presented in [7]

$$G(x,x') = G^0(x-x') - \int_S E(x,y)G^0(y-x')dy ,$$

where $G^0(x - x')$ is the zero Green function

$$E(x,y) \overset{def}{=} \sum_{n=0}^{\infty} e_n(x)e^n(y) .$$

Each sufficiently smooth function can be expanded in a series of bases. Functions concentrated on the interval S of the elastic energy operator Φ that determine the internal characteristics of the medium can be expanded in a series of bases

$$e^m(x) = \frac{i}{\Phi'_-(k_m)}\int_0^{x+S} \Phi_-(x-x')e^{-ik_m x'}dx' ,$$

where $e_n(x)$ is a functional basis, $\{e^m(x), e_n(x)\}$ is the biorthogonal basis.

The factorization Φ gives the functions of $\Phi_\pm(k)$-type

$$\Phi_\pm(k) = \exp\left[\frac{1}{2\pi i}\int \frac{Im\,\Phi(k')}{\pm k - k'}dk'\right]$$
$$\Phi_+(k) = \int_0^l \psi_+(x)(1-e^{-ikx})dx$$
$$\Phi_-(k) = \int_{-l}^0 \Psi_-(x)(1-e^{-ikx})dx = \Phi_+(-k)$$

Thus, the biorthogonal basis is completely determined by the assignment of force constants.

The introduction of k- and ω-representations allows us to study the frequency spectrum of AE signals. The shape of the propagating AE signal depends not only on the offset time, but also on the frequency ω. Therefore, along with the displacement functions, their Fourier images should also be considered.

For the Fourier transform, the same notation should be kept, but with the argument k

$$\langle q|u\rangle = \int \overline{q(x)}u(x)dx = \frac{1}{2\pi}\int \overline{q(k)}u(k)dk$$

where $q(x) = \Sigma_n q(n)\delta_B(x - na)$, $q(k) = B(k)\Sigma_n q(n)e^{-inak}$.

Here, $B(k)$ is the segment characteristic function $B[-\pi/a \le k \le \pi/a]$, on which the Fourier transform is different from zero, $\delta_B(x - a)$ is a function representing the one-dimensional kernel of the identity operator.

Function $q(n)$ decreases as $n \to \infty$ and reflects the damping of elastic waves in the medium. At the same time, it enters a linear functional depending on $u(n)$

$$\langle q|u\rangle \overset{def}{=} \sum_n \overline{q(n)}u(n)$$

The force constants $\Phi(n, n')$ are functions of two variables (x, t), defined on a square lattice with a step a. Multiplying them on the left by $u(n)$ and on the right by $\upsilon(n')$, we will get the form $\langle u \mid \Phi \mid \upsilon\rangle$ linear in the second argument and antilinear in the first one.

The invariance of the form $\langle u \mid \Phi \mid \upsilon\rangle$ relative to n-, x- and k-representations implies from the invariance of the scalar product

$$\langle u \mid \Phi \mid \upsilon \rangle \overset{def}{=} \sum_{nn'} \overline{u(n)} \Phi(n, n') \upsilon(n') =$$

$$\iint \overline{u(x)} \Phi(x, x') \upsilon(x') dx dx' = \frac{1}{2\pi} \iint \overline{u(k)} \Phi(k, k') \upsilon(k') dk dk'$$

$$\langle u \mid \Phi \mid \upsilon \rangle \overset{def}{=} \sum_{nn'} \overline{u(n)} \Phi(n, n') \upsilon(n') =$$

$$\iint \overline{u(x)} \Phi(x, x') \upsilon(x') dx dx' = \frac{1}{2\pi} \iint \overline{u(k)} \Phi(k, k') \upsilon(k') dk dk'$$

The functions $\Phi(n)$, $\Phi(x)$ and $\Phi(k)$ are one-dimensional kernels of the elastic energy operator Φ. Each form of the elastic energy operator Φ can be uniquely assigned to a linear operator by defining it as

$$\langle \overline{q \mid \upsilon} \rangle = \langle \upsilon \mid \Phi \mid u \rangle ,$$

i.e. the kernel of the form is also the kernel of the elastic energy operator defined by it.

The second main task of the propagation of AE signals in coupled continuous media is their consideration in the boundary regions specified by displacements rather than forces.

The process of propagation of AE signals in media will be considered as continuous. What follows when $\Delta x \to 0$:

$$y(x + \Delta x) = \lambda \int_a^b k(x + \Delta x, t) y(t) dt + f(x + \Delta x) , \qquad (5)$$

or subtracting (5) from (4)

$$y(x + \Delta x) - y(x) = \lambda \int_a^b \left[k(x + \Delta x, t) - k(x, t) \right] y(t) dt +$$
$$+ f(x + \Delta x) - f(x)$$

we have the Fredholm equation of the second kind with a difference kernel.

Each dynamic variable $u(y)$ can be represented by a linear operator. Each linear operator corresponds to a linear equation, on the basis of which its own values are found.

The linear form of the displacement $u(y)$ relative to the variable y is written as

$$U(y) = P_{a_0} y_a + P_{a_1} y'_0 + \ldots + P_{a_{n-1}} y_a^{(n-1)} + P_{b_0} y_b + \ldots + P_{b_{n-1}} y_b^{(n-1)}$$

where $y_a, y'_a, \ldots, y_a^{(n-1)}$; $y_b, y'_b, \ldots, y_b^{(n-1)}$ are values of the vector function and its derivatives, $Pa_0, \ldots, Pa_{n-1}$, Pb_0, Pb_1, … and Pb_{n-1} are fixed linear operators in complex vector space R^m.

For any function y, linear differential equation $l(y)$ can be represented as the result of applying the operator $P_j(x)$ to the vector $y^{(n-j)}(x)$

$$l(y) = P_0(x) y^{(n)} + P_1(x) y^{(n-1)} + \ldots + P_n(x) y ,$$

where $1/P_0(x)$, $P_1(x)$, … , $P_n(x)$ are operator functions.

The same differential expression can generate different differential operators depending on the choice of boundary conditions.

In the case when several forms of particle displacement $U_1(y)$, $U_2(y)$, … , $U_q(y)$ are given, the boundary problems of determining the energy spectrum of AE signals in conjugate media are reduced to a system of integral equations

$$\begin{cases} C_1 U_1(y_1) + C_2 U_1(y_2) + \ldots + C_n U_1(y_n) = 0 \\ C_1 U_2(y_1) + C_2 U_2(y_2) + \ldots + C_n U_2(y_n) = 0 \\ \ldots \\ C_1 U_m(y_1) + C_2 U_m(y_2) + \ldots + C_n U_m(y_n) = 0 \end{cases}$$

where C_1, C_2, … , C_n are constants.

Its solution reduces to finding the linear operator L and the eigenfunctions $y_1, y_2, \ldots, y_n$, for which this operator becomes zero.

The linear operator L with the definition area $y \in D$ is generated by the differential expression $l(y)$ and the boundary conditions

$$Ly = ly .$$

The eigenvalues of the operator L are those values of the parameter λ, which determine the energy spectrum of the AE signal, for which the homogeneous boundary-value problem has nontrivial solutions, i.e.

$$l(y) = \lambda y, \qquad \upsilon = 1, 2, \ldots, m .$$

The spectral characteristics of AE signals can be found if the law of their distribution on the frequency $\omega(k)$ is known. With the total number of atoms in the chain $N \to \infty$ the vibration spectrum becomes continuous and the frequency distribution function $\nu(\omega)$ has the form [7]:

$$\upsilon(\omega) = \frac{a}{\pi} \left| \frac{dk}{d\omega} \right|$$

For a chain with the interaction of nearest neighbors, the frequency distribution function takes the form:

$$\upsilon(\omega) = \frac{2}{\pi \sqrt{\omega_{max}^2 - \omega^2}}$$

Maximum ω_{max} is reached at $k = \pm^{\pi}/_{a}$. At $\omega < \omega_{max}$ AE signals will propagate in both media. Signals with high frequencies decay exponentially. The energy spectrum of developing defects is determined by the structure of the interfaced media and the forces determining the occurrence of AE signals: internal forces holding the structure in an equilibrium state, forces destroying the structure due to the imperfection of the material, and force constants determined by the physical and mechanical properties of the material.

Since equation (3) includes the quadratic term ω^2, which reflects the frequency characteristic of particle motion in contiguous media, as well as the quantity ω, which varies over time, as a concrete example, the corresponding Fredholm equation of the second kind can be written as:

$$y(x)-\lambda\int_0^1(xt+x^2t^2)y(t)dt=f(x),$$

where $k(x, t) = xt+x^2t^2$ is equation lernel, $a_x = x$, $b_x = x^2$; $a_t = t$, $b_t = t^2$ are border conditions.

Here, the integration limits from zero to one denote the propagation zone of the AE signal. Then the Fredholm equation takes the form:

$$y(x)=\lambda(x\int_0^1 ty(t)dt+x^2\int_0^1 t^2y(t)dt)+f(x).$$

If the following notations are introduced

$$\upsilon_1=\int_0^1 ty(t)dt,\qquad \upsilon_2=\int_0^1 t^2y(t)dt,$$

then

$$y(x)=\lambda(x\upsilon_1+x^2\upsilon_2)+f(x).$$

After integration, a system of linear algebraic equations for υ_1 and υ_2 will be obtained

$$\begin{cases}\upsilon_1=\lambda\left(\dfrac{\upsilon_1}{3}+\dfrac{\upsilon_2}{4}\right)+W_1\\ \upsilon_2=\lambda\left(\dfrac{\upsilon_1}{4}+\dfrac{\upsilon_2}{5}\right)+W_2\end{cases}$$

where $W_1 = \int_0^1 xf(x)dx$, $W_2 = \int_0^1 x^2f(x)dx$.

Therefore,

$$\begin{cases}\left(1-\dfrac{\lambda}{3}\right)\upsilon_1-\dfrac{\lambda}{4}\upsilon_2=W_1\\ -\dfrac{\lambda}{4}\upsilon_1+\left(1-\dfrac{\lambda}{5}\right)\upsilon_2=W_2\end{cases}$$

The solution to this system exists only when the following condition is fulfilled:

$$\boldsymbol{det}\begin{pmatrix}1-\dfrac{\lambda}{3} & -\dfrac{\lambda}{4}\\ -\dfrac{\lambda}{4} & 1-\dfrac{\lambda}{5}\end{pmatrix}\neq 0.$$

Characteristic numbers will be

$$\left(1-\frac{\lambda}{3}\right)\left(1-\frac{\lambda}{5}\right)-\frac{\lambda^2}{16}=0,$$

$\lambda_1 = 4(16-\sqrt{241})$, $\lambda_2 = 4(16+\sqrt{241})$.

If $\lambda = 4$ and $f(x) = x^2$, it will be

$$\begin{cases}-\dfrac{1}{3}\upsilon_1-\upsilon_2=\dfrac{1}{4}\\ -\upsilon_1+\dfrac{1}{5}\upsilon_2=\dfrac{1}{5}\end{cases}$$

Therefore, $\upsilon_1 = -15/64$ and $\upsilon_2 = -11/64$.

Taking into account the coefficients found, the second type Fredholm equation takes the form:

$$y(x)=4\left[x\left(-\frac{15}{64}\right)-\frac{11}{64}x^2\right]+x^2,$$

where $y(x)$ is the triggered AE signal from the precursor of the material destruction.

The values of λ and $y(x)$ are eigenvalues and an eigenfunction of the kernel $k(x, t)$.

The conversion of discrete signals caused by stresses in the structure of materials into a continuous analytic function is possible through a set of δ-functions using Fourier series.

It will be interesting to apply the Fourier transform to this boundary value problem

$$F(\omega)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}y(x)e^{-i\omega x}.$$

Substituting the expression $y(x)$ into this formula, its frequency spectrum through delta functions of the first and second order will be found

$$F(\omega)=-\frac{27}{8}\sqrt{\frac{\pi}{2}}\delta''(\omega)+\frac{15}{2}\sqrt{\frac{\pi}{2}}\delta'(\omega).$$

It follows that the better the function is concentrated in time, the more it is blurred in the private area. When the scale of the function changes, the product of the probability densities of the time and particular ranges remains constant, which is confirmed by the results of studies carried out in [11].

In [12], the results of experimental studies on the establishment of interconnections of the occurrence of AE signals to changes in the structure of materials caused by different loading of steel St3sp samples are presented (Fig. 4).

Both graphs show the structure of the spectrum of AE signals, which is in accordance with the value of the characteristic number $\lambda = 4$. Some inconsistencies between the numerical values of the amplitudes in the theoretical and experimental spectrum are due to the absence of coating in the experiment, as well as ignoring the parameters of the physical and mechanical properties of bases and coatings in the theoretical model.

The initiation of AE signals, caused by changes in the structure, in the first approximation can be considered using the evolutionary concepts of the dislocation theory as lattice damage (Fig. 5).

The presence of defects in the lattice causes diffusion of atoms, increasing their mobility, which manifests itself in the initiation of AE signals.

The first basic condition that the elastic energy operator must satisfy is the invariance of the particles of the material structure relative to translation. The elastic energy does not change during the conversion $u(x) \to u(x) + u_0$, because the distance between the particles does not change (Fig. 5a). The property of translational invariance of energy is manifested in the existence of longitudinal, shear and spin vibrations and in the quantitative redistribution of energy from the precursors of AE signals.

The second main condition for the existence of the elastic energy operator is its hermiticity $\Phi(n,n') = \Phi(n',n)$, which is based on the fact, that the operator defined by the kernels can be extended to a wider class of functions characterizing the formation of defects. This can be shown experimentally in the form of exits to the surface of displacing atoms (Fig. 5b), vacancies (Fig. 5c), edge and screw dislocations, linear and planar defects, heterovalent substitution, antistructural defects (Fig. 5d).

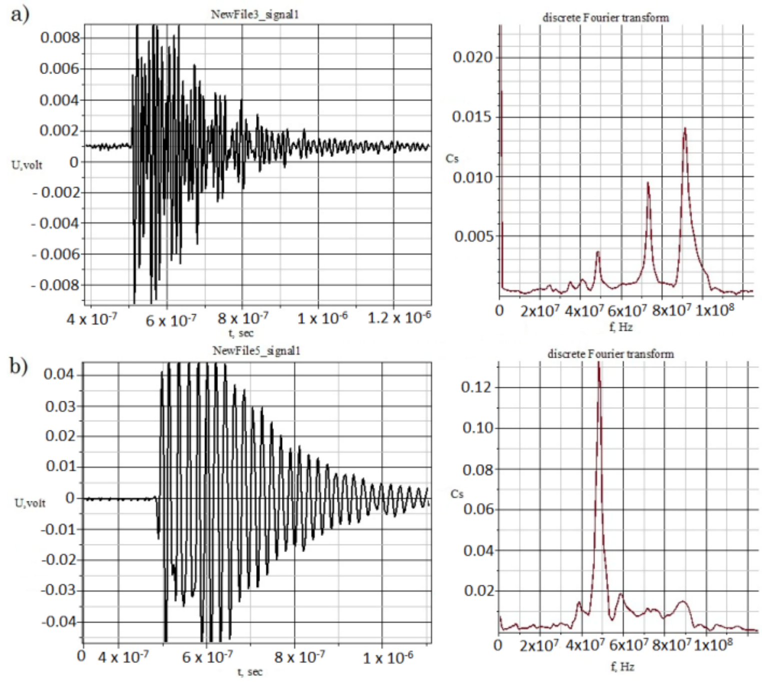

Fig. 4 – Characteristics of AE signals and their processing using Fourier transform: a) 1650 kg, b) 2170 kg

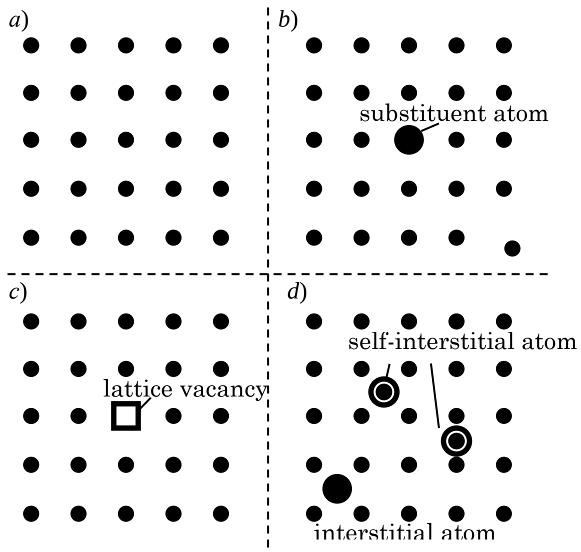

Fig. 5 – Simple defect structures: *a*) ideal lattice, b) substituent impurity, c) lattice vacancy, *d*) interstitial admixture and two self- interstitial defects

The third basic condition, which the elastic energy operator must satisfy, is its homogeneity, which is based on its invariance with respect to the shift. To determine the force constants, it is necessary to have additional information on the structure of interatomic interactions inside the base and the coating, as well as on the nature of the coupling fields of both boundary media.

The analytical apparatus for determining the energy spectrum of the precursors of the occurrence of AE signals in conjugate media makes it possible to consider discrete and continuous models with the use of space-time and frequency-wave representations at the same time as a single formalism.

4. CONCLUSIONS

With local changes in the structure and breakage of atomic bonds, the sources of AE signals appear. Fourier transforms allow the region of changes in the structure of the material, in which the changes under the action of a disturbing force took place, to be transferred to the congruent region of initiation of AE signals.

Representation of the equation of particle motion during the development of internal defects in the form of Fourier series with a basis of eigenfunctions using the Green function allows spectral analysis of differential operators and decomposition of given functions by their own value.

In the case when the forces initiating the appearance of AE signals are specified in the boundary region, the Fredholm equation of the second kind with a symmetric kernel is most applicable. In the case when displacements of particles of the medium are specified in the boundary region, which determine the conditions for propagation of AE waves, the Fredholm equation with a difference kernel is most applicable.

The experimental verification of the main theoretical models of the energy spectrum of AE signals in a medium with a developing defect, at different stages of the load diagram, showed their consistency and satisfactory agreement in the basic details of the energy spectrum structure.

The conditions for the existence of an elastic energy operator for initiating AE signals: homogeneity, invariance of the particles of the material structure relative to translation, the hermitability of the operator allows them to be associated with the formation of metal crystal lattice defects and can be used in predicting the stages of metal constructions failure.

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Енергетичний спектр сигналів акустичної емісії в сполучених суцільних середовищах

В.В. Марасанов[1], А.В. Шарко[2], А.О. Шарко[1]

[1] *Херсонський національний технічних університет, вул. Бериславське шосе, 24, 73008 Херсон, Україна*
[2] *Херсонська державна морська академія, проспект Ушакова, 20, 73009 Херсон, Україна*

Одним з невирішених проблем моделювання наноструктур і фізики наносистем є закономірності існування пружної енергії ініціювання операторів АЕ сигналів. Розглянуто поширення сигналів акустичної емісії зі зв'язком двох безперервних середовищ. Основними змінними в рівняннях руху частинок є сила, що визначає виникнення акустичної емісії і зміщення частинок середовища, що визначає поширення пружної хвилі. Наведено методологічну основу для знаходження енергетичного спектра сигналів акустичної емісії у зв'язаних середовищах з використанням функції Гріна і перетворення Фур'є. Обґрунтовано умови існування оператора пружної енергії для ініціювання сигналів акустичної емісії. Першою базовою умовою, яку повинен задовольняти оператор пружної енергії, є інваріантність частинок структури матеріалу щодо перетворення. Другою основною умовою існування оператора пружної енергії є її герметичність. Третя основна умова, яку повинен задовольняти оператор пружної енергії, – його однорідність, яка ґрунтується на її інваріантності щодо зсуву. Встановлено однозначну відповідність між характеристиками дискретної структури матеріалів і параметрами поширення сигналів АЕ в сполучених середовищах. На основі порівняння розрахункових характеристичних чисел спектру та діаграми навантаження для розривних випробувань було показано, що енергетичний спектр сигналів акустичної емісії в зв'язаних безперервних середовищах повністю визначається силовими константами матеріалу та силами, що ініціюють появу сигнали акустичної емісії. Представлений енергетичний спектр сигналів акустичної емісії в спряжених моделях безперервних середовищ дозволяє асоціювати їх з утворенням дефектів кристалічної решітки металу і може бути використаний для прогнозування стадії руйнування матеріалу. Експериментальна перевірка основних теоретичних моделей енергетичного спектру сигналів АЕ в середовищі з дефектом, що розвивається, на різних етапах діаграми навантаження показала їх узгодженість і задовільну згоду в основних деталях структури енергетичного спектру.

Ключові слова: Акустична емісія, Сигнали, Спектр, Власні значення, Власні функції, Рівняння Фредгольма другого роду, Перетворення Фур'є.