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MATHEMATICAL MODEL AND INFORMATIVE PARAMETERS OF THE MAGNETOELASTIC ACOUSTIC EMISSION SIGNAL

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Summary. *A mathematical model of the magnetoelastic acoustic emission (MAE) signal in the form of a random impulse flow is proposed and considered. The impulse and time informative parameters of the MAE signal are allocated and algorithms of their estimation are developed. The influence of external force loads applied to lamellar samples made of nickel and 19G steel on the change of the informative parameters of the MAE signals is examined. For a steel sample we estimate the distribution of pulse amplitudes and intervals between adjacent pulses of the MAE signals at different values of the applied load. The obtained estimations we approximated by exponential curves. These dependencies can be used as calibration curves for the diagnostics of residual stresses in ferromagnetic objects of long-term operation.*

Key words: *magnetoelastic acoustic emission, mathematical model, informative parameters, ferromagnetic materials.*

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Introduction. Nowadays the problem of diagnostics the products and structural elements state, as well as equipment, whose service-life is due and needs to be replaced, is of great importance for the industry of Ukraine, for the space, chemical, power engineering oil, gas-pipe transport and mechanical engineering in particular. Caused by the long-term operation in the severe conditions, physical chemical changes take place, contributing to poor mechanical properties, quality and reliability.

The promising method for the diagnostics of such objects made of ferromagnetic materials is the method of magnetoelastic acoustic emission (MAE), which is caused by the remagnetization of the ferromagnetic structural material due to the Barkhauser effect [1,2]. The advantage of the method, as compared with that of acoustic-emission as diagnostics is that there is no need to apply additional load, to stop operation or to change the operation mode of the element being under control.

From the literature review we can conclude, that there is a lack of theoretical or methodic specification [2, 3]. Looking for new additional informative parameters of the signal is a pressing problem, the solving of which will make it possible to improve the diagnostics efficiently of ferromagnetics taking advantage of the MAE method.

Physical aspects of the MAE signal formation. P.L. Weiss delivered the hypothesis that the ferromagnetic material consists of separate areas of simultaneous magnetization-domains, here the direction of the magnetic atom moments being parallel, but different from that of the moments direction of the adjacent area [4]. In 1926 Lengmure was the first to state the notion of the domain wall: these are layers of the non-parallel spins dividing the domains of different magnetization orientation. Depending on the crystal symmetry the domain walls are classified according to the degree measure of the angle, in which the magnetization direction changes in the adjacent domains, e.g. the 1800 th and non-1800 th domain walls [5]. In the real ferromagnetic crystal the thickness of the domain wall is specified by the condition of the exchange energy balance and that of the magnetic anisotropy energy.

The domain structure is the result of different types of interrelations being available in the ferromagnetic materials. For the finite size crystals the unidomain structure is energy disadvantageous, because the demagnetization field is available. Energy advantageous is the state, when ferromagnetic sample is divided into some areas of the simultaneous magnetization in such a way, that the resultant magnetization of the whole sample equals zero.

In real crystals, because of the available structural defects and internal stresses, the domain wall is located so, that the increase of the crystal free energy is minimum. That is why the 180^{0} th walls are located in the places, where the inner stresses, the values of the efficient constant of the magnetic anisotropy and the energy surface density is minimum, instead of the 180^{0} th domain wall, where the stress changes the sign corresponding the change of the axis direction of the light magnetization in the adjacent domains.

Resulted from the outside magnetic field, the ferromagnetic demagnetized state is the energy disadvantages, new component of magnetization appears, which is different from that of zero, and it starts being magnetized. Such magnetization results in the increase of the domains volume and the change of the simultaneous magnetization direction I_S of some domains during their rotation. The processes accompanying it can be reversible and irreversible depending on the fact, what amount of energy in the form of heat is dissipated.

The heterogeneous materials are characterized by the hysteresis caused by the walls displacement as during the motion different inclusions, mechanical loads and dislocations block the domain walls. The detailed investigation of the magnetization curve in the area of the domain walls displacement testified, that under smooth change of stress of the outside remagnetized field magnetization in the sample is of jump-like nature. Such changes of magnetization were called the Barkhausen jump (BJ) or the jumps of remagnetization (Fig. 1). The domain wall coordinates x_O is equal to the balance value of the magnetic field H . If it is increased, the reverse displacement of the wall will last until it, being out of its balanced state, is in the point of coordinate x_A, in which the maximum of some internal pressure is obtained, resulted from the gradient of the energy surface density of the domain wall $\partial\gamma/\partial x$, and the outside field reaches the critical value $H = H_{кр}$.

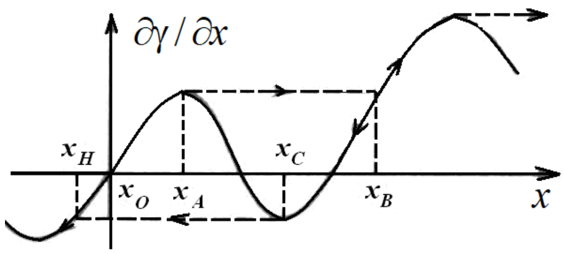


Figure 1. The mechanism of the jump-like motion of the domain walls [6]

The further motion of the domain wall can be without increasing the outside magnetic field till the point with coordinate x_B, as for the values range $x_A < x < x_B$ the inside pressure is less than that outside. As the result, the domain wall is of jump-like motion from the point x_A to the point x_B and magnetization is of the jump-like nature and changes in some values. Such process is irreversible, because if the magnetic field is decreasing further, the wall will not return again from the point x_B to the point with the coordinate x_A, but will be reversibly transferred to the position x_C and will be in the jump-like motion to the point x_H .

Displacement of the domain boundaries caused by the outside magnetic field depends greatly on the coordinate dependence of the surface energy density of the boundary layer:

$$\gamma = (K_{ef} A / a)^{1/2}, \tag{1}$$

where the effective constant of the magnetic anisotropy is:

$$K_{ef} \approx aK + b\lambda\sigma, \tag{2}$$

and K – is the constant of the nature anisotropy;
λ – is magnetostriction constant;
σ – are the inside mechanical stresses;
a and b – are the constants of the given crystal [7].

The free energy of the ferromagnetic crystal is the minimal, if the domain boundaries are located in the places corresponding the minimal inside forces, if the magnetic field is not available. They include, first of all, inside stresses caused by the deformation of the crystal lattice or different types heterogeneities, e.g. inclusions.

Thus, the Barkhausen effect (BE) is specified by the stochastic motion of the domain walls, which is the sequence of jumps of the 1800 th domain walls, that is, is of the snow-slip nature under slow magnetization. The jumps dynamics depends on the material microstructure, demagnetization field, stresses, etc. [8].

Radiation of the elastic waves – MAE, caused by BE is associated with the magnetostriction deformations in ferromagnetics, taking place in the body local areas, where the sudden changes of the non-1800 th domain walls location, being affected by the outside magnetic field, are noticed [9-11]. The main parameters specifying BJ are the jump duration, the change of the remagnetization volume, resulted from one jump, and its size. The change of magnetization $\Delta m = M_S \Delta V$, resulted from the single jump of the non-1800 th domain wall, is called the BJ size in the ferromagnetic materials. Maximum displacements caused by the jumps of the non-1800 th domain walls, can be estimated according to the dependence(3) [12].

$$u_{\max} \sim \lambda_S \frac{M}{M_S} (\lambda + 2\mu \cos^2 \theta) V' / (4\pi\rho c_1^3 r), \tag{3}$$

where λ and μ – are the Lame' constants;
ρ – is the medium density; deformation tensor component;
c_1 – is the longitudinal wave velocity;
M – is magnetization;
λ_S – is magnitostriction constant of the ferromagnetic material;
θ – is the angle being measured from the area corresponding the longitudinal elastic wave propagation, caused by the change of the domain structure in ferromagnetic.

It is clear from [3], that the amplitude values of the MAE signal are proportional to the transformation deformations (the multiplier λsM/Ms) and to the rate of change of the remagnetization area volume V1. Effective registration of the MAE signal can be done using the piezoelectric transformer.

Mathematic model of the MAE signal. Analysis of the mechanism for the MAE signals generation makes it possible to specify their main characteristics [13]: random in time appearance of some events (random flow of impulses); time restriction (finity), energy weakness; random amplitude. These features make possible to treat the signals within the model of the random impulse flow [3].

In this case the signal can be presented as the impulses superposition, the shape of which is described by the determined function $F(t)$ normalized in unit for maximum, here the impulses can differ in the amplitude. The corresponding impulse flow will be presented as follows:

$$X(t) = \sum_{k,i} A_{ki} F_{ki}(t - t_{ki}), \tag{4}$$

where T – is the remagnetization period;
$k = 1, 2, \ldots$ – is the period number;
t_{ki} – is the random moment of the i^{th} impulse appearance in the K – period $(k-1)T < t_{ki} \le kT$, $i = 1, 2, \ldots$;
A_{ki} – is its random amplitude;
t_{ki} – is the appearance moment being assumed conventionally, because it is not necessary that $F_{ki}(t - t_{ki}) = 0$, if $t < t_{ki}$.

It is expected, that $F(t)$ is directed to zero very quickly, if $|t| \to \infty$, that is why $\int_{-\infty}^{\infty} |F_{ki}(t - t_{ki})| < \infty$. The time moments t_{ki} can be connected with any specific point – with any of extremums $F(t)$ or with any of points of transition over zero, if they are available, etc [3].

More general treatment of the random impulse flow is, that except the amplitude, the shape of the impulses themselves is assumed to be random, which depends on the aggregate of some finite number *m* parameters $\mu = \{\mu_1, \ldots, \mu_m\}$.

$$X(t) = \sum_{k,i} A_{ki}(\mu) F_{ki}(t - t_{ki}, \mu). \tag{5}$$

The MAE signal depends on the parameters of the remagnetized field (the results of the stress amplitude, frequency and the signal shape) and is sensitive to the structural changes of the ferromagnetic material, heat treatment mode, plastic deformation, residual stresses, hydrolisation, etc.). The material being degradated changes its domain structure, influencing the change of the MAE parameters [14-15]. It was found experimentally, that the plastic deformation of the material influences the strength of MAE the most, the hydrolisation factor being less effective, depending on its concentration in the ferromagnetics [16-17].

Informative parameters of the MAE signal. Basing on the model (4) the impulse informative parameters of the magnetoelastic emission signal can be specified. They include the probability density of the impulse amplitude distribution *p*(*A*), the sum of the impulse amplitudes during the k^{th} period of remagnetization $\sum_i A_{ki}$, the MAE signal envelopes generated during the period of remagnetization, as well as the parameters set of the impulses shape $\mu = \{\mu_1, \ldots, \mu_m\}$. The time informative parameters are the impulse flow intensity *n*(*t*), $q(\vartheta)$ – the probability density of the intervals distribution $\vartheta_{ki} = t_{k(i+1)} - t_{ki}$ between the adjacent impulses of the flow, resultant impulses calculation during the k^{th} period of remagnetization $N_k = \sum_i H(t - t_{ki})$, where $H(\cdot)$ – is the Havyside's function.

The informative components of the MAE signal generally include the discontinuous and continuous jammings, that is why the model (4) can be presented as follows:

$$X(t) = \sum_{k,i} A_{ki} F(t - t_{ki}) + \sum_j B_j G_j(t - t_j) + S(t) + \gamma(t)\,. \tag{6}$$

here B_j – is the amplitude;
$G_j(t - t_j)$ – is the function of the discontinuous jamming shape, resulted from the mechanism operation, electric model in the electrical network, electromagnetic impulses, etc.;
$S(t) = S_0 \sin\omega t$ – is the discontinuous harmonic jamming, resulted from the frequency of the industrial electric network (S_0 – its amplitude, ω – frequency);
$\gamma(t)$ – is the stationary discontinuous random jamming, initiated by the effect of radio-frequency jammings and noises of the transmission channel, which can be described within the correlation theory with the mathematic expectation $\overline{\gamma}$, dispersion D_γ, the one-dimentional distribution density $f(\gamma)$ and the normalization auto-correlation function $r_\gamma(\tau)$ (τ – the time shifting).

Jammings can sufficiently distore the results of the signal informative parameters estimation. That is why, in order to obtain the true information for the correct engineering diagnostics, it is worth being done properly.

Estimation of the MAE signal parameters. Some important conditions concerning the emission signals, resulted from the influence of the mechanical, physical, chemical and other factors on the object being investigated, are of special importance. These signals, as a rule, in many cases do not satisfy the conditions of "good statistics": random error of estimation the statistical parameters of the signal can not exceed the admissible error, which guarantees to some probability the identification of the defect or estimation of characteristics of the crack-forming process. It is caused by the fact, that the duration of the signal implementation for a given product or structure is limited greatly. Generation of the emission signals is not controlled and stops, when the investigation object has been ruined. In the case of the MAE signal the random error can be decreased in any case thanks to the increase of the remagnetization field.

The estimation of such traditional characteristics of the MAE signal as the amplitude sum during j – implementation (Fig. 2) will look like:

$$\hat{A}_{\Sigma j}(A_{th}) = \sum_{i=1|(T(j-1)\le t_{ji} < Tj)} A_{ji|(A_{ji} > A_{th})}\,. \tag{7}$$

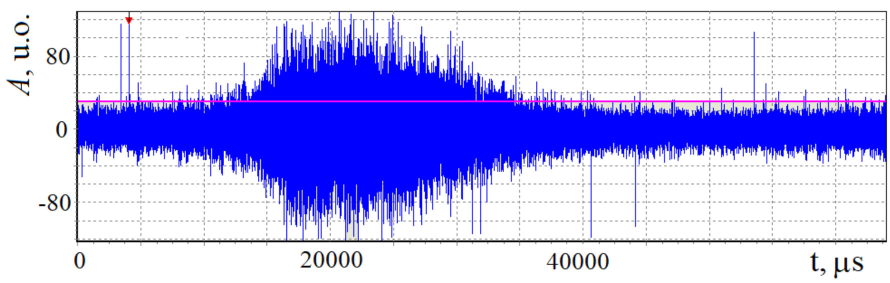


Figure 2. The MAE signal implementation during the magnetization of a lamellar ferromagnetic sample: the frequency of magnetization is 9 Hz, the amplitude of the induction of a magnetic field equals 0,8 T

In the expression (7) the impulse amplitudes, which are greater than the threshold value Aij>Ath exceeding the noises level, are summarized. In order to decrease the random error, having used the signal *M* implementation, for the estimation of the amplitude sum we will obtain the expression:

$$\hat{A}_{\Sigma a}(A_{th}) = \frac{1}{M}\sum_{j=1}^{M}\sum_{i=1|(T(j-1)\le t_{ji}<Tj)} A_{ji|(A_{ji}>A_{th})}, \tag{8}$$

and for its dispersion:

$$D_{\hat{A}_{\Sigma a}(A_{th})} = \frac{1}{M} D_{\hat{A}_{\Sigma j}(A_{th})}. \tag{9}$$

The dispersion is decreased in *M* times as compared with that of the estimation during one implementation $D_{\hat{A}_{\Sigma j}(A_{th})}$, and, as a result, the estimation error can be as small as possible.

Similar to the estimation of the resultant calculation during the j- implementation, the following expression can be obtained:

$$\hat{N}_{\Sigma j}(A_{th}) = \sum_{i=1|((A_{ji}>A_{th}),T(j-1)\le t_{ji}<Tj)} H(t-t_{ji}), \tag{10}$$

during *M* – implementations:

$$\hat{N}_{\Sigma a}(A_{th}) = \frac{1}{M}\sum_{j=1}^{M}\sum_{i=1|((A_{ji}>A_{th}),T(j-1)\le t_{ji}<Tj)} H(t-t_{ji}), \tag{11}$$

which can result in the decrease of dispersion in *M* times as compared with the estimation dispersion during one implementation $D_{\hat{N}_{\Sigma j}(A_{th})}$

$$D_{\hat{N}_{\Sigma a}(A_{th})} = \frac{1}{M} D_{\hat{N}_{\Sigma j}(A_{th})}. \tag{12}$$

Estimation of the mean amplitude in the time range of the j^{th} period *T* of remagnetization is:

$$\hat{A}_j(l, A_{th}) = \frac{1}{N_j(l)}\sum_{i=1}^{N_j(l)} A_{ji|(A_{ji}>A_{th})}(l), \tag{13}$$

Nj(l) – is the number of impulses registered in the time window [(l-1)Td, lTd];
Td – is the signal discretization interval;
$l = 1, 2, \ldots$ – is the window number.

Thus, for the M implementation:

$$\hat{A}_a(l, A_{th}) = \frac{1}{M}\sum_{j}^{M}\frac{1}{N_j(l)}\sum_{i=1}^{N_j(l)} A_{ji|(A_{ji}>A_{th})}(l), \tag{14}$$

which decreases the dispersion in M times as well.

The estimation of the impulses number in the time window during the j th implementation:

$$\hat{N}_j(l, A_{th}) = \sum_{i=1|((A_{ji}>A_{th}),T_d(l-1)\le t_{ji}<T_d l)}^{N_j(l)} H(t - t_{ji}) , \tag{15}$$

and during *M*- implementations:

$$\hat{N}_a(l, A_{th}) = \frac{1}{M}\sum_{j=1}^{M} \sum_{i=1|((A_{ji}>A_{th}),T_d(l-1)\le t_{ji}<T_d l)}^{N_j(l)} H(t - t_{ji}) . \tag{16}$$

Beside traditional parameters of the MAE signal the MAE signal envelope is of great importance too [14, 18], the characteristics of its shape and duration in particular.

The estimation of envelope according to the algorithm of sliding mean values is found according to the formula:

$$\hat{s}_j(k) = \frac{1}{N}\sum_{i=0}^{N-1} \left| s_j(k+i) \right| . \tag{17}$$

here $|s(i)|$ – is the module of the i – reading of the signal;

N – is the number of the signal readings being averaged (the width of the window averaging), $\hat{s}(k)$ – the *kth* value of the envelope.

It is averaged as well according to the number of samplings M registered as the result of the experiment:

$$\hat{s}_a(k) = \frac{1}{M}\sum_{j=1}^{M} \frac{1}{N}\sum_{i=0}^{N-1} \left| s_j(k+i) \right| . \tag{18}$$

The estimation of the envelope according to the algorithm of the sliding average-quadratics is found according to the formula:

$$\hat{s}_j(k) = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} s_j^2(k+i)} , \tag{19}$$

for the M samplings:

$$\hat{s}_a(k) = \frac{1}{M}\sum_{j=1}^{M} \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} s_j^2(k+i)} . \tag{20}$$

here $s^2(i)$ – is the square of the signal i^{th} reading;

N – is the number of the signal readings, which are averaged (the width of the averaged window);

$\hat{s}(k)$ – is the *kth* value of the envelope estimation.

The estimations dispersion (18) and (20) averaged according to the number of samplings M decreases and equals:

$$D_{\hat{s}_a(k)} = \frac{1}{M} D_{\hat{s}_j(k)},$$

When the MAE signal is treated as the impulse random process (4), it is possible to use and estimate the statistical characteristics additionally, that is, shape, parameters, moments and entropy of the amplitude and time distribution of the random flow of impulses.

The amplitude distribution of the MAE signal can be estimated using the multichannel amplitude analyzer with l_0 the adjacent amplitude “windows” of the ΔA width each, or using software according to the digitized data and the device for the signal selection. Then, the histogram for the amplitude distribution of the MAE signal during the j – implementation will look like:

$$\hat{h}_j^A(l, A_{th}) = \begin{cases} 0, \ A \le A_{th} \\ N_{jl}^A / \sum_{l=1}^{l_0} N_{jl}^A, \ A \in (A_{th} + (l-1)\Delta A, l\Delta A] \\ 0, \ A > A_{th} + l_0 \Delta A \end{cases}. \tag{21}$$

Here the lower boundary of the dynamic range of the impulses amplitude will be determined by the threshold value Ath, which depends on the noises level, and the upper $(A_{th} + l_0 \Delta A)$ – by the analyzer rank, Nl – is the number of readings in the channel of number *l*. The averaged histogram during the *M* implementations is:

$$\hat{h}_a^A(l, A_{th}) = \frac{1}{M} \sum_{j=1}^{M} \hat{h}_j^A(l, A_{th}), \tag{22}$$

with the estimation dispersion:

$$D_{\hat{h}_a^A(l, A_{th})} = \frac{1}{M} D_{\hat{h}_j^A(l, A_{th})}. \tag{23}$$

The estimation of the first and second moments of the amplitude distribution equals respectively:

$$\hat{A} = \Delta A \sum_{l=1}^{l_0} (l \cdot \hat{h}^A(l, A_{th})), \tag{24}$$

And

$$\hat{A}^2 = (\Delta A)^2 \sum_{l=1}^{l_0} (l^2 \cdot \hat{h}^A(l, A_{th})). \tag{25}$$

The histogram of the interval distribution between the adjacent impulses of the MAE signals flow during j – implementation will look like:

$$\hat{h}_j^{\vartheta}(l, A_{th}) = \begin{cases} N_{jl}^{\vartheta}(l) / \sum_{l=1}^{l_0} N_{jl}^{\vartheta}(l),\ (A > A_{th}) \wedge (\vartheta \in (\Delta\vartheta(l-1), \Delta\vartheta l]) \\ 0, \vartheta > \Delta\vartheta l_0 \end{cases}, \quad (26)$$

and the averaged histogram during M implementation looks as follows:

$$\hat{h}_a^{\vartheta}(l, A_{th}) = \frac{1}{M}\sum_{j=1}^{M} \hat{h}_j^{\vartheta}(l, A_{th}), \quad (27)$$

thus, correspondingly, the dispersion is:

$$D_{\hat{h}_a^{\vartheta}(l, A_{th})} = \frac{1}{M} D_{\hat{h}_j^{\vartheta}(l, A_{th})}. \quad (1)$$

Estimation of the first moment of the interval distribution is as follows:

$$\hat{\vartheta} = \Delta\vartheta \sum_{l=1}^{l_0} (l \cdot \hat{h}^{\vartheta}(l, A_{th})), \quad (29)$$

and that second moment looks like:

$$\hat{\vartheta}^2 = (\Delta\vartheta)^2 \sum_{l=1}^{l_0} (l^2 \cdot \hat{h}^{\vartheta}(l, A_{th})). \quad (30)$$

To check the hypothesis concerning the distribution law itself, the available in the literature so-called matching criteria being divided conventionally into two classes – general and special, can be used. General criteria can be divided into three main groups [19]:

1 – those being based on the study of the difference between the theoretical distribution density and the empiric histogram;

2 – those being built on the estimation of the distance between the theoretical and empiric functions of the probabilities distribution;

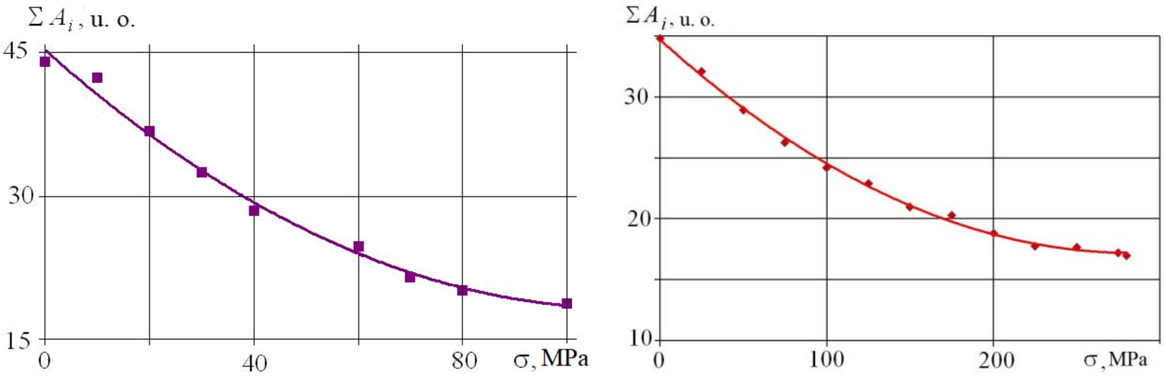
3 – correlation-regression criteria being based on the study of the correlation and regression bonds between the empiric and theoretical ordinal statistics.

Comparison of the empire histogram of the random value distribution with its theoretical density is the basis of criteria χ^2, empty intervals by Barnet-Eison, etc. [19].

But it is known, that the estimation of the distribution density according to the histogram gives the shifting error [20]. It is possible to reduce the value of shifting while narrowing the internal ΔA or $\Delta\vartheta$. It will result in the increase of the dispersion of the histogram estimation, which can be decreased by the increasing of the number of averaging implementations.

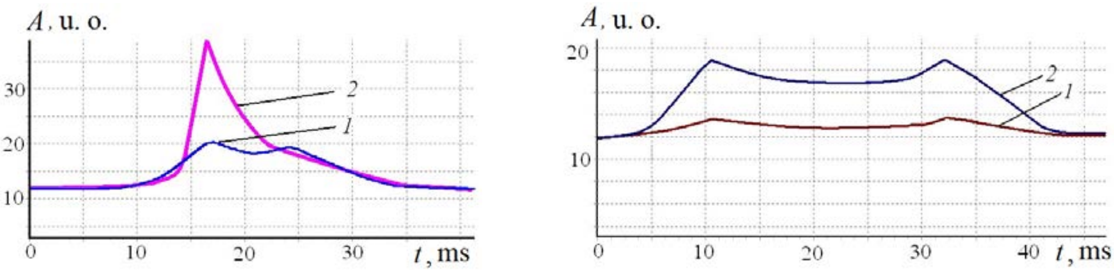
Experimental testing of the estimation parameters of the MAE signal. Thus, the MAE signal is multiparameterous. It is very important to develop the algorithms of the statistic estimation of the MAE signal parameters with the further determination of the correlation bonds between them and parameters specifying the state of the investigated ferromagnetic object [18].

The experimental investigations were carried out to estimate the influence of the applied mechanical stresses on the change of the MAE signal parameters and to determine the corresponding correlation bonds. Equal size and shape nickel and steel samples were under the action of the tension stress (for nickel the tension σ being changed from 0 MPa till 110 MPa, for steel – till 280 MPa), which was remagnetized with the outside field and MAE signals were registered. According to the obtained results the dependence of the MAE signals sum on the induction amplitude of the remagnetized field *B* and with the increase of the applied stresses the decrease of the amplitudes sum for both samples is noticed. The characteristics of the envelope shape and dependence of the MAE signals duration on the applied outside load as well as the induction amplitude of the remagnetization field, have been investigated (Fig. 4,5). When σ and *B* are increased, the change of the envelope shape is noticed (one sharp clear peak is formed in the nickel sample and two peaks in the steel samples) and sufficient decrease of the amplitude and the MAE signals duration.



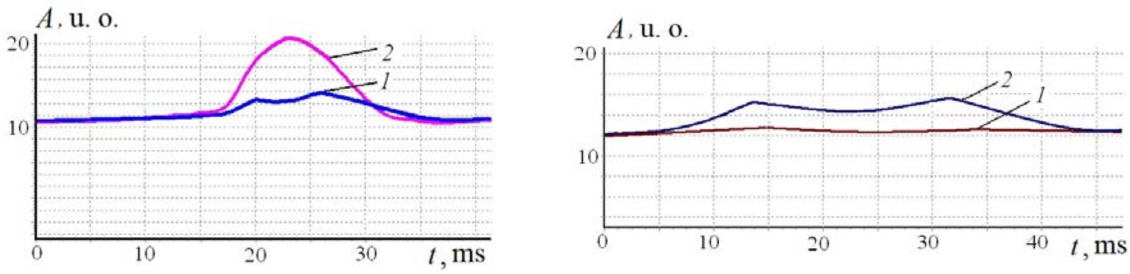
a *b*

Figure 3. The dependence of amplitudes sum of the MAE signals on stresses caused by an external load: (*a*) a nickel plate (*B* = 0,35 T); (*b*) 19G steel plate (*B* = 1,28 T)



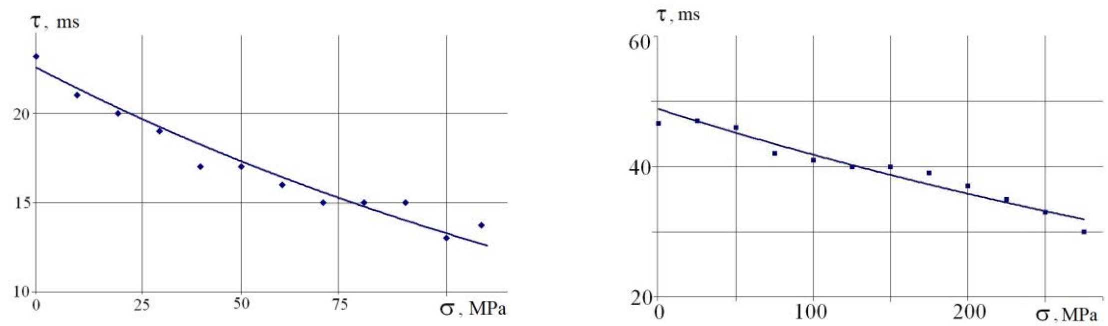
a *b*

Figure 4. Features of the MAE envelope shape on changes of the amplitude of the magnetizing field induction *B* and σ = 0: (*a*) a nickel sample (*1* – 0,2 T, *2* – 0,35 T); (*b*) a steel sample (*1* – 1,08 T, *2* – 1,8 T)



a *b*

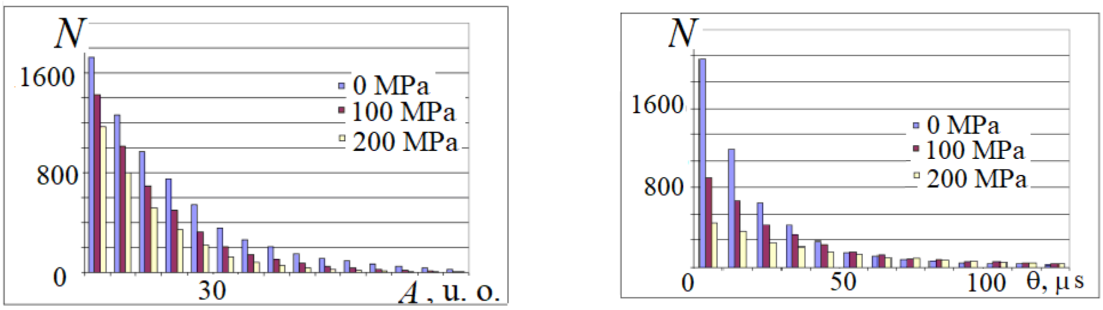
Figure 5. Features of the MAE envelope shape on changes of the amplitude of the magnetizing field induction *B*: (*a*) a nickel sample (σ = 110 MPa, *1* – 0,2 T, *2* – 0,35 T); (*b*) a steel sample (σ = 175 MPa; *1* – 1,08 T, *2* – 1,8 T)



a *b*

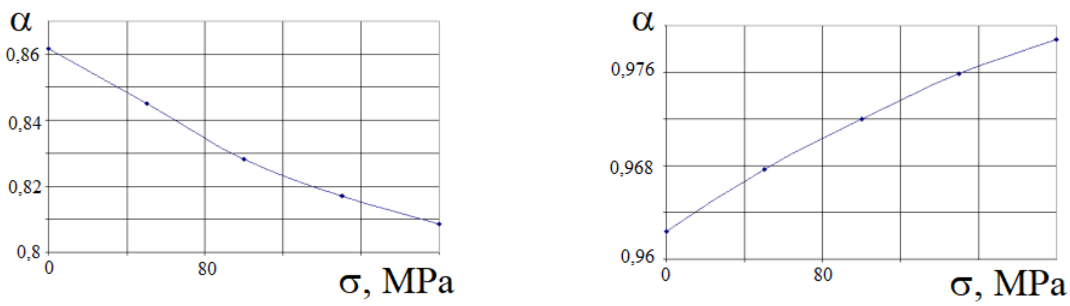
Figure 6. The dependence of the MAE signals duration on the applied stresses: (*a*) a nickel sample (B = 0,35 T); (*b*) a steel sample (B = 1,8 T)

For the steel sample, according the proposed earlier algorithm (21) and (26), the estimations of the impulse amplitude distributions and intervals between the adjacent impulses of the MAE signals for different values of the applied loads, have been found (Fig. 7). The obtained estimations have been approximated by the exponential curves and dependences of the attenuation coefficients of the approximated exponents on the applied load have been built (Fig. 8), which can be used as the gradation curves for the diagnostics of the residual stresses in the ferromagnetic objects of long-term operation (Fig .8).



a *b*

Figure 7. The estimation of a probability distribution density (histogram) of the amplitudes (*a*) and the intervals between adjacent pulses (*b*) of the MAE signal for a steel sample at different loads



a *b*

Figure 8. The dependence of the attenuation coefficients of the approximation exponentials of the distribution probabilities estimation of the amplitudes (*a*) and the intervals between adjacent pulses (*b*) of the MAE signal for a steel sample at different loads

These dependences are characterized by the strength to some experimental factors influencing the amplitude characteristics of the signal (the coefficient of strengthening of the MAE signal, the quality of the contact of the acoustic emission transformer with the object surface, the transformer direction diagram), as compared with the similar dependence of the signal amplitude sum on the value of the applied load (Fig. 3).

The outside mechanic stresses, applied to the investigated ferromagnetic samples, cause the change of the magnetic structure. The magnetic-elastic energy under stresses is proportional to $\lambda\sigma\sin^2\alpha$, where λ – is the magnetostriction constant, α – is the angle between the directions of the magnetization vector $\vec{M}$ and the applied stresses to the control object σ. The influence of these stresses causes the turning $\vec{M}$ parallel towards the direction σ for minimizing the magnetic-elastic energy. It causes the increase of the general area of the 1800th domain walls in the material volume due to the decrease of areas of non- 1800th ones, and the decrease of the MAE signals amplitude [13]. Increase of the amplitude of the MAE signal, when the induction amplitude of the remagnetization field increases, can be explained by the improvement of intensity of the domain walls jumps. Operation of the ferromagnetic structures at the enterprises of industry is almost impossible in real conditions without the influence of loads and deformations on the material of the working medium.

Conclusions. Mathematic model of the MAE signal as the random impulse flow has been proposed and interpreted. The impulse and time informative parameters of the MAE signal have been specified and the algorithm of their estimation has been developed.

The influence of the outside force loads, applied to the lamellar samples, made of nickel and steel 19Г, on the change of the informative parameters of the MAE signals, has been investigated. It was found, that when the applied outside stresses increase, the sum of the signal amplitudes decreases under the constant value of the induction amplitude of the remagnetization field, the change of the envelope shape and decrease of the MAE signals duration take place.

For the steel sample the estimations of the impulse amplitude distributions and the intervals between the adjacent impulse of the MAE signals under different values of the applied loads have been found. The obtained estimations have been approximated by the exponential curves and the dependences of the attenuation coefficients of the approximated exponents on the applied load have been built, which can be used as the grading curves for the diagnostics of the residual stresses of the ferromagnetic objects of long-term operation.

Generalization of the presented results makes possible to conclude, that the MAE method is sensitive enough for the investigation of the stress-strain state of the ferromagnetic materials. It testifies the possibility to apply this method to carry out non-fracture control of the structural elements made of ferromagnetic materials.

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МАТЕМАТИЧНА МОДЕЛЬ ТА ІНФОРМАЦІЙНІ ХАРАКТЕРИСТИКИ СИГНАЛУ МАГНЕТОПРУЖНОЇ АКУСТИЧНОЇ ЕМІСІЇ

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Резюме. *Запропоновано та обґрунтовано математичну модель сигналу магнетопружної акустичної емісії (МАЕ) у вигляді випадкового імпульсного потоку. Виділено імпульсні та часові інформативні параметри сигналу МАЕ й розроблено алгоритми їх оцінювання. Досліджено вплив зовнішніх силових навантажень, прикладених до пластинчастих зразків, що виготовлені з ніколу та сталі 19Г, на зміну інформативних параметрів сигналів МАЕ. Встановлено, що зі збільшенням прикладених зовнішніх напружень сума амплітуд сигналів зменшується за сталого значення амплітуди індукції перемагнічувального поля; спостерігається також зміна форми обвідної та скорочення тривалості сигналів МАЕ. Для стального зразка знайдено оцінки розподілів амплітуд імпульсів та інтервалів між суміжними імпульсами сигналів МАЕ за різних значень прикладеного навантаження. Апроксимовано отримані оцінки експоненційними кривими. Побудовано залежності коефіцієнтів загасання апроксимувальних експонент від прикладеного навантаження, які можна використовувати як градуювальні криві для діагностування залишкових напружень у феромагнетних об'єктах тривалої експлуатації. Узагальнення наведених результатів дозволяє зробити висновок, що метод МАЕ є достатньо чутливим за дослідження напруженого стану феромагнетних матеріалів. Це свідчить про можливість застосування даного методу для проведення неруйнівного контролю елементів конструкцій, що виготовлені з феромагнетних матеріалів.*

Ключові слова: *магнетопружна акустична емісія, математична модель, інформативні параметри, феромагнетні матеріали.*

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