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STATISTICAL PROPERTIES OF SIGNAL PULSE AMPLITUDE OF MAGNETOELASTIC ACOUSTIC EMISSION

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The amplitude of the pulses of the magnetoelastic acoustic emission signal is shown to be distributed according to the exponential law, which makes it possible to use its attenuation parameter as an informative one for the diagnostics of ferromagnetic objects. The dependences of the attenuation coefficients of the approximate exponents of the obtained amplitude distributions estimates on the applied load are constructed, which can be used as calibration curves for the diagnostics of residual stresses in long-term operation ferromagnetic objects.

Keywords*: magnetoelastic acoustic emission signal, magnetic field, probability density of amplitude distribution, residual stress.*

СТАТИСТИЧНІ ВЛАСТИВОСТІ АМПЛІТУДИ ІМПУЛЬСІВ СИГНАЛУ МАГНЕТОПРУЖНОЇ АКУСТИЧНОЇ ЕМІСІЇ

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Розглядаючи сигнал магнетопружної акустичної емісії в межах випадкового імпульсного потоку, запропонували використовувати як інформативні параметри його амплітудного розподілу. Для дослідження статистичних властивостей амплітуди сигналу виконано експериментальні дослідження на сталевому (Ст.3) та нікелевому зразках та за однією реалізацією знайдено гістограми розподілів амплітуд імпульсів. Для перевірки гіпотези щодо конкретного закону розподілу використано критерій χ^2, який ґрунтується на порівнянні емпіричної гістограми розподілу випадкової величини з її теоретичною густиною. Показано, що амплітуда імпульсів сигналу магнетопружної акустичної емісії розподілена за експоненційним законом, який дає змогу використати параметр загасання як інформативний під час діагностування феромагнетних об'єктів. Для апробації нового інформативного параметра до нікелевого та сталевого зразків однакових розміру та форми прикладали зусилля одновісного розтягу (для нікелю напруження змінювали від 0 МПа до 110 МПа, для сталі до 280 МПа), перемагнечували їх зовнішнім полем та реєстрували сигнали магнетопружної акустичної емісії. Знайдено оцінки розподілів амплітуд імпульсів для різних значень прикладеного навантаження. Побудовано залежності коефіцієнтів загасання апроксимувальних експонент одержаних оцінок амплітудних розподілів від прикладеного навантаження, які можна використовувати як градуювальні криві для діагностування залишкових напружень у феромагнетних об'єктах тривалої експлуатації.

Ключові слова: *сигнал магнетопружної акустичної емісії, магнетне поле, густина ймовірності розподілу амплітуд, залишкові напруження.*

For diagnostics of long-operating elements and products made of ferromagnetic materials, the method of magnetoelastic acoustic emission (MAE), combining two physical principles: magnetization by an external magnetic field and registration of elastic waves arising from the discontinuous movement of 90° domain walls in ferromagnets, is a promising one [1–7]. The advantages of the method are: no need to apply additional load as well as no need to stop the operation or change the operating mode of the element that is subject to testing.

In previous studies a high sensitivity of the MAE signal parameters to structural changes in the material of a ferromagnetic object, plastic deformation, residual stresses, hydrogen, etc. was determined. This necessitated the development and implementation of the MAE method as a potentially effective means of non-destructive testing.

From the literature review it follows that, as a rule, such informative parameters of the MAE signal as the sum of the amplitudes of the signal pulses and the final count are used [8–15]. When interpreting the MAE signal as a pulsed random process [16], one can additionally use and estimate statistical characteristics, namely, the shape, parameters, moments, and entropy of the amplitude and time distribution of a random pulse stream.

The amplitude distribution of the MAE signal can be estimated using a multichannel amplitude analyzer with l_0 adjacent amplitude "windows" of width ΔA each or program-based results digitized data from the signal sampling device. Then the histogram of the amplitude distribution of the MAE signal over j realization will look:

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

Here, the lower boundary of the dynamic range of the pulse amplitudes is determined by the threshold value A_{th}, which depends on the noise level, and the upper $(A_{th} + l_0 \Delta A)$ digit capacity of the analyzer, N_l is the number of samples in the channel with number l. Histogram was averaged over M realizations:

$$\hat{h}_a^A(l, A_{th}) = \frac{1}{M} \sum_{j=1}^{M} \hat{h}_j^A(l, A_{th}) \tag{2}$$

with estimation variance:

$$D_{\hat{h}_a^A(l, A_{th})} = \frac{1}{M} D_{\hat{h}_j^A(l, A_{th})} . \tag{3}$$

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

$$\hat{A} = \Delta A \sum_{l=1}^{l_0} (l \cdot \hat{h}^A(l, A_{th})) \tag{4}$$

and

$$\hat{A}^2 = (\Delta A)^2 \sum_{l=1}^{l_0} (l^2 \cdot \hat{h}^A(l, A_{th})) . \tag{5}$$

To test the hypothesis regarding a specific distribution law, one can use the so-called statistical fitting criteria known from literature, which are conditionally divided into two classes – general and special. General criteria can be divided into three main groups [17, 18]:

1 – based on the study of the difference between the theoretical distribution density and the empirical histogram;

2 – built on the estimation of the distance between theoretical and empirical probability distribution functions;

3 – correlation-regression criteria, based on the study of correlation and regression relationships between empirical and theoretical ordinal statistics.

A comparison of the empirical histogram of the distribution of a random variable with its theoretical density is the basis of the χ^2 criteria, empty intervals [17]. However, it is known that estimation of the distribution density over the histogram gives an offset error [18]. The bias value can be reduced by a corresponding narrowing of the

ΔA interval. This leads to an increase in the variance of the histogram estimate, which can be reduced by increasing the number of averaging realizations.

To study the statistical properties of the MAE signal amplitude, experimental studies were performed on steel (Ст.3) and nickel samples and, according to algorithm (1), histograms of the distribution of the MAE signals pulse amplitudes were found using one implementation (Fig. 1*a*, *b*). The general view of the histograms gives grounds for choosing the exponential distribution law as the null hypothesis.

If to test the hypothesis about the exponentiality of the law of amplitude distribution use the χ^2 criteria and the estimate $\hat{h}(l)$. Then it is necessary to calculate the statistics [18]

$$\chi^2 = N_\Sigma \sum_{l=1}^{l_0} (\hat{h}(l) - p_l)^2 / p_l \,, \tag{6}$$

where $p_l = \int_{(l-1)\Delta A}^{l\Delta A} \lambda \cdot exp(-\lambda A) dA$ is the theoretical probability of the amplitude getting into the *l*-th window. Here λ is the distribution parameter, N_Σ is the sample volume.

Statistics (6) has the distribution χ^2 [18]

$$p(x) = \frac{(1/2)^{k/2}}{\Gamma(k/2)} x^{k/2-1} e^{-x/2} \,, \tag{7}$$

where k is the number of degrees of freedom.

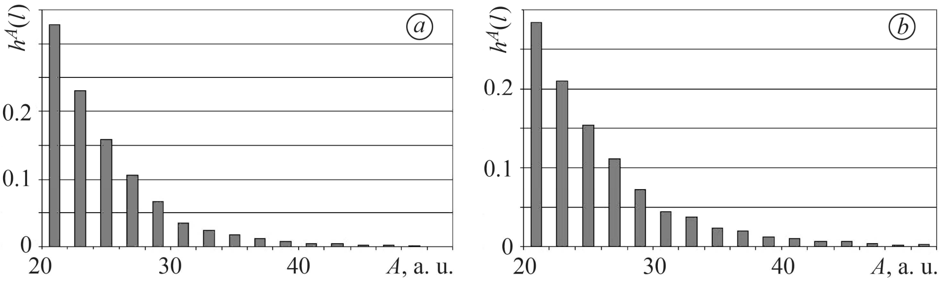

Fig. 1. Histograms of the amplitude distributions of the MAE signal for steel (*a*) and nickel (*b*) samples: magnetization frequency 9 Hz, magnetization field induction amplitude 0.8 and 0.4 T, respectively.

If the distribution of a random variable is known with precision to its parameters, then $k = l_0 - 1$. If the parameters of a hypothetical distribution law are estimated by the sampling itself, the number of degrees of freedom is reduced by the number of parameters m, that are estimated. The exponential distribution is one-parameter, so $m = 1$ and, accordingly, $k = l_0 - 2$.

The power of criterion χ^2 is greatly influenced by the number of partition intervals (window width) of the histogram. In practice, it is generally accepted that statistics χ^2 can be used if $N_\Sigma p_l \geq 5$ [17].

The rule for testing the hypothesis is simple [17, 18] if:

$$N_\Sigma \sum_{l=1}^{l_0} (\hat{h}(l) - p_l)^2 / p_l > \chi^2_\alpha \,, \tag{8}$$

then at the level of significance α, the hypothesis of an exponential distribution law is rejected with confidence $(1-\alpha)$. Otherwise, the hypothesis is accepted at a given level of significance. Here χ^2_α is the α-quantile of distribution (7).

To build a histogram of the distribution of amplitudes for a steel sample, we take the number of intervals $l_0 = 16$. We set the confidence probability $\alpha = 0.95$, the sample size being $N_\Sigma = 3371$. The intermediate calculation results are given in Table 1 by which we calculate the criterial value $\chi^2 = 15.8$. For the chosen confidence probability $\alpha = 0.95$ and the number of degrees of freedom $k = 16 - 2$, from the table presented in [17] we find the critical value of the statistic of the criterion $\chi^2_{0,05} = 23.7$. Since the critical value turned out to be greater (23.7 > 15.8) than that calculated according to statistical data, the hypothesis of sampling belonging to an exponential distribution must be accepted.

Table 1. Intermediate results of the calculation of the value of χ^2 for the sampling of the signal obtained in the steel sample experiment

break intervals	number of realizations	$\hat{h}(l)$	p_l	$(\hat{h}(l) - p_l)^2 / \nu_l$
20	1106	0.328093	0.343365	0.000679
22	778	0.230792	0.225608	0.000119
24	533	0.158113	0.148235	0.000658
26	358	0.1062	0.097398	0.000795
28	226	0.067042	0.063995	0.000145
30	119	0.035301	0.042048	0.001083
32	80	0.023732	0.027628	0.000549
34	59	0.017502	0.018153	2.33E-05
36	40	0.011866	0.011927	3.15E-07
38	25	0.007416	0.007837	2.26E-05
40	15	0.00445	0.005149	9.5E-05
42	13	0.003856	0.003383	6.62E-05
44	8	0.002373	0.002223	1.02E-05
46	7	0.002077	0.001461	0.00026
48	3	0.00089	0.00096	5.07E-06
50	1	0.000297	0.000631	0.000177
Σ	3371	1	1	0.004688

For the histogram averaged over $M = 10$ realizations, the calculated criterion value is $\chi^2 = 6.1$, that is, the condition of sampling belonging to the exponential distribution is enhanced.

To construct a histogram of the amplitude distribution for a nickel sample, we also specify the number of intervals $l_0 = 16$, the confidence probability $\alpha = 0.95$. The sample volume is $N_\Sigma = 4576$, and the intermediate calculation results are shown in Table. 2, by which we calculate the criterion value $\chi^2 = 20.3$. Since the critical value turned out to be greater (23.7 > 20.3) than that calculated from the statistics, the hypothesis of sampling belonging to the exponential distribution must be accepted.

Table 2. Intermediate results of the calculation of the value of χ^2 for the sampling of the signal obtained in the nickel sample experiment

break intervals	number of realizations	$\hat{h}(l)$	p_l	$(\hat{h}(l)-p_l)^2/\nu_l$
20	1300	0.284091	0.2961	0.000487
22	963	0.210446	0.208751	1.38E-05
24	703	0.153628	0.14717	0.000283
26	512	0.111888	0.103755	0.000637
28	330	0.072115	0.073148	1.46E-05
30	202	0.044143	0.05157	0.001069
32	172	0.037587	0.036357	4.17E-05
34	106	0.023164	0.025632	0.000237
36	88	0.019231	0.01807	7.45E-05
38	55	0.012019	0.01274	4.07E-05
40	47	0.010271	0.008981	0.000185
42	32	0.006993	0.006332	6.9E-05
44	29	0.006337	0.004464	0.000786
46	16	0.003497	0.003147	3.88E-05
48	10	0.002185	0.002219	5.04E-07
50	11	0.002404	0.001564	0.000451
Σ	4576	1	1	0.00443

For the histogram averaged over $M = 10$ realizations, the calculated criterion value is $\chi^2 = 14.5$ that is, the condition of sampling belonging to the exponential distribution is enhanced.

The calculations make it possible to state that the pulse amplitude of the MAE signal is distributed according to the exponential law, and its parameter λ can be used as informative for the diagnostics of ferromagnetic objects by the MAE method.

To test a new informative parameter, uniaxial tensile forces were applied to the samples of nickel and steel (for nickel, the tension varied from 0 MPa to 110 MPa, for steel to 280 MPa), they were magnetized by an external field, and MAE signals were recorded (Fig. 2).

Based on the results of the above studies on the exponential law of the distribution of the MAE signal pulse amplitudes, the dependences of the attenuation coefficients λ on the applied load are constructed, which can be used as calibration curves for the diagnostics of residual stresses in long-time exploitation ferromagnetic objects (Fig. 3).

These dependences are characterized by resistance to a number of experimental factors that affect the amplitude characteristics of the signal (gain of the MAE signal, the quality of the contact of the acoustic emission transducer with the surface of the object, the transducer directivity diagram), compared with a similar dependence of the sum of the signal amplitudes on the applied load value [13–16].

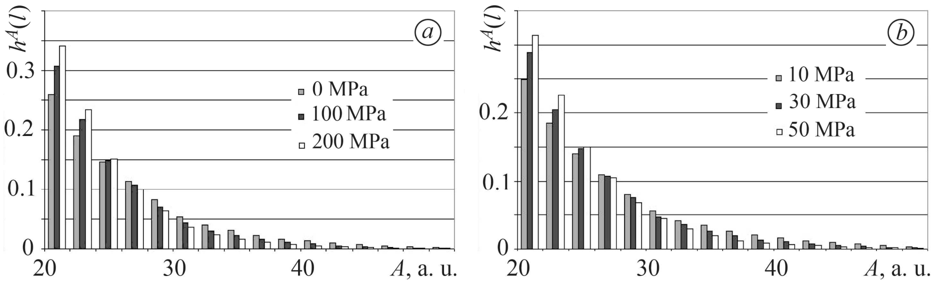

Fig. 2. Estimates of the probability density of the distribution of amplitudes (histograms) for the MAE signal for various sample loads: *a* – steel; *b* – nickel.

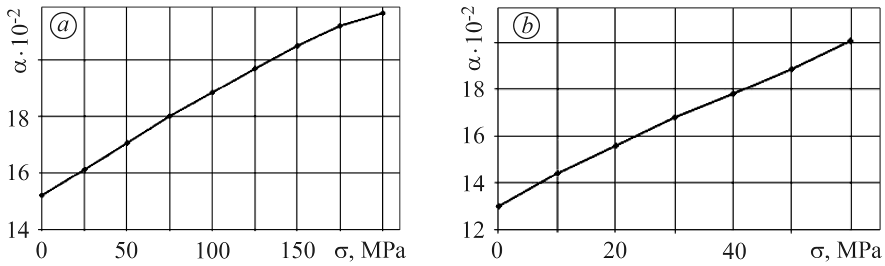

Fig. 3. Dependence of the attenuation coefficient of the approximating exponent of the estimate of the amplitude distribution on the applied load for the samples: *a* – steel; *b* – nickel.

CONCLUSIONS

Studies allow us to state that the amplitude of the pulses of the MAE signal is distributed according to the exponential law, and, therefore, its parameter λ can be used as informative in the diagnostics of ferromagnetic objects.

For plate steel and nickel samples, that are subjected to tensile load, estimates of the distribution of pulse amplitudes for various values of the applied load are found. The dependences of the approximating exponents attenuation coefficients of the obtained estimates of the amplitude distributions on the applied load are constructed, which can be used as calibration curves for the diagnosis of residual stresses in ferromagnet objects of long-time exploitation.

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