Information and kinetic approach to the acoustic emission diagnostics of technical facilities

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Abstract. The analysis of trends in the development of resource assessment methods is given, a multi-level information-kinetic approach to acoustic emission diagnostics is described and its methodological relationship with the traditional experimental method of resource assessment is shown. The informative multi-model diagnostic parameters associated with various scale level strength characteristics of structural materials and resource technical objects are given. The examples of resource assessment of welded joints and rolling bearings are considered.

1. Introduction
The reasonable assessment of residual life is a necessary component of a set of preventive measures that ensure the reliability and safety of operation. Long-term prediction of residual life is made on the basis of an assessment of their pressure-strain-state, parameters of fatigue curves, hypotheses of damage summation-up, methods of fracture mechanics and non-destructive control [1-10]. The variety of defects, types of loading, the complexity of operation and the behavior of hazardous industrial facilities leads to forecast uncertainty, which implies the need for destructive testing of reference samples with various concentrators [5-8, 24-28].

The traditional destructive approach to the assessment of the resource has already covered most of the construction materials, due to it a good database of empirical data has been created, but the problem of taking into account the influence of the defectiveness of a specific product operating under unique industrial conditions remains. The creation of a sample of this model, identical to the object, is a very difficult task, and in connection with the use of space-geometry-geometric systems in the framework of traditional concepts of mechanics. The criteria for the similarity of defects weakly correlating with the parameters of the accumulation of damage and retaliation, the traditional methods for solving the problem do not provide the expected result. The search for the possibility to remove the uncertainty with non-destructive observation methods of the process of growth of damage is distinguished among other methods of acoustic emission as the most promising method. However, to evaluate a resource under industrial conditions of significant noise and the influence of interference, the AE method also requires revision [11, 12].

The solution of the long-term acoustic emission forecasting of the residual life of hazardous technical objects seems possible based on the information-kinetic approach developed by the author of the article [13, 14, 18-23], which focuses on the information of AE signals optimization of control, allowing formulating criteria for metrological and strength identity (similarity) of objects and control results, to create operational methods for assessing their strength characteristics tick and residual
resource prediction. The purpose of the work was to uncover the connection between the information-kinetic approach and current trends in the development of methods for assessing the resource of hazardous technical objects and the traditional empirical approach, as well as justifying its pre-so-so rationality on the basis of comparison with existing ones.

2. Idea of problem solution

The analysis of modern approaches to the development of methods of acoustic emission diagnostics of the state of technical objects (figure 1) allows dividing them into:

- statistical, based on comparison with the permissible values of the primary parameters of the AE (number of pulses, total amplitude, energy of AE signals, etc.) or their distribution parameters, various statistical invariants and variations, regression, spectral and wavelet analysis of the results of registration of AE signals;
- physical, based on the laws of mechanics or micro fracture mechanisms, the kinetic concept of strength, the principles of information optimization of AE control technologies and physical models of AE parameters.

The increase in the sensitivity, the increase in the amount of primary information about AE signals, and automation of control, modernization of the instrumental part of the method led to the domination of a statistical approach in AE diagnostics. However, weak noise immunity, short-term prediction and laboriousness of learning statistical methods have sharpened the understanding of the need for fundamental methodological development, optimizing the search for the connection of a wide range of primary parameters of AE control with performance criteria to abilities, indicators of reliability and resource. In this regard, the increasing interest of AE control specialists is attracted by physical approaches.

Approaches to AED Security

1. Statistical approach

1.1. Statistical invariants

- $M_{ap}$ - average pulse spacing
- $Q_{ap}$ - standard deviation

1.2. Statistical variations

- changes in scattering ellipses of AE parameters, frequency and amplitude distributions, time intervals between pulses, standard deviation, coeff. var. wavelet analysis

1.3. Regression analysis

2. Physical approaches

2.1. Mechanical

- Crack rate $V=\frac{a}{k}$ (Paris-Erdogan model)
- Coating rate $N=\frac{a}{k}$ (Daugam model)

Where $A_0=2.38\times10^{-10}$, $L_0=3.8\times10^{-10}$, (metrological spread $dN_0$ 5th order)

$m$ - local dynamic indicator

2.2. Kinetic

Model of homogeneous microcracking

$\frac{dC(t)}{dt} = C(t) \left( \frac{C(t)}{C(t)+C_{m}} \right)^{0.1-0.01} \Delta C ^{1}$

$N = \frac{A}{N_0}$

$N_0 = 10^{3}$ (metricalogical spread $dN_0$ 6th order)

2.3. Informational kinetic

Micromechanical model of AE parameters

$\xi(t) = k_2 \int_0^1 \left[ \int_0^t \left( V \left( \frac{\partial \xi}{\partial t} \right) \right) dt \right] d\phi$

$\text{fatigue curve}$

$N = \frac{A}{N_0}$ (metricalogical spread $dN_0$ 2nd order)

Figure 1. Classification of approaches to ensure the reliability of the method of acoustic emission diagnostics.
Focusing on the parameters of the process of the development of cracks, the mechanical approach (section 2.1, figure 1) is most widely used [11, 12]. However, it is short-term, since it does not consider the object until the formation of a crack and is not always informative in the conditions of strength heterogeneity of the material and metrological heterogeneity of the control. The kinetic approach [15] (section 2.2, figure 1) is more informative, since it divides the destruction process into two stages, adding to the crack growth stage the previous stage of fine destruction, considers the hierarchy of the process and uses a steady concentration sign of destruction. Based on the hypothesis of linear summation of damages and stability of the critical value of relative concentration of microcracks (C*/C0≈10^-3 in section 2.2, figure 1), the approach allows predicting the resource according to the results of observation of the first, longest stage long before the formation of a crack or fragmentation of the material, which makes it long-term. The tendency of the further development of the approach has been outlined through the modeling of durability heterogeneity and the separation of the first stage of the destruction process into stages with differing dissipative properties and the results of the competition of acts of destruction and relaxation of the material [16]. However, the absence of specific quantitative methods for estimating the duration of the stages and the high uncertainty of the parameters in the resource estimation formulas (section 2.2, figure 1) that depends on interference makes the diagnosis method no longer possible. Sufficiently informative with respect to the resource. The information-kinetic approach (section 3.3, figure 1) is associated with the modeling of the strength inhomogeneity of the material and the metrological non-rational nature of control, specific methods of identifying stages stages of dispersed fracture, information filtering of AE signals and complex analysis of information obtained on various scale levels of information on the strength properties of the material necessary to assess the resource of the control object.

The effectiveness of the approach is shown on products made of composite materials, building structures, metallurgical billets, various types of welded joints, pressure vessels, structures of hoisting- and-carrying machines, and cast metal structures of rolling stock elements. The requirements and criteria for the optimization of AE control have been formulated, which have become the basis of new ways to assess the performance and predict the life of hazardous technical facilities [13].

Considering the dependence of the characteristics of strength, resource, parameters of the process of destruction and AE materials on the result of competition simultaneously occurring in a heterogeneous material processes of destruction and plastic deformation of structural elements [17], the resource of the majority of long loaded materials, structures and structures according to the approach is determined by the elastic process of microcracking. Reference representatives of the strength properties of the product are its structural elements, selected from their total number by kinetic and temporal similarity criteria using AE control. The resource object technical assessment is based on the experimental determination of the moment and intensity of elastic uniform destruction of representative structural elements by recording the AE signal (figure 2). Informative about the moment of destruction is the time t of this registration, information about the number of destroyed structural elements carries the parameter ξ, which can be the number N_e of recorded pulses of a discrete AE, the total score N of AE, the relative total amplitude or a combination of these parameters.

The time dependence ξ(t) under the conditions of the strength inhomogeneity of the material has the form of a multilevel model:

\[ ξ(t) = k_{AE} C_{0} \int_{\omega_{0}}^{\omega_{\infty}} \Psi(\omega) \left[ 1 - \exp \left( -\int_{0}^{t} dt / \Theta(U(t), \omega(t)) \right) \right] d\omega \]  

(1)

where k_{AE} is the acoustic emission coefficient (AEC) responsible for the “metrological” concentration conversion C scattered in the material gaps in the structural elements of the scale level preceding the formation of the main crack and fragmentation of the material into the ξ AE parameter that has the
meaning of the acoustically active volume of the material influenced by noise and factors destabilizing the relationship between $C$ and $\xi$. Its value

$$k_{AE} = V \int \int \int F(\Delta t, f, u) du df dt$$

(2)

where $V$ is the controlled volume of the material, the macroscale value; $F(\Delta t, f, u)$ is the density function of the distribution of AE signals over the duration of the pauses $\Delta t$, frequency $f$, and amplitude $u$; $C_0$ is the initial concentration of structural elements, as a rule, on a micrometric scale; $\theta$ is the time of microelement destruction, given by Zhurkov formula.

**Figure 2.** Model of the AE source and interpretation of the value that includes the path factors of the AE signal of the acoustic emission coefficient: a is model of the AE signal source and factors of the AE recording, $\sigma^*$ strength limit, $E$ is modulus of elasticity, $D$ is characteristic size of the structural element; b is amplitude distribution of AE signals; c is the frequency distribution of AE signals; d is the probability of recording AE signals at a given amplitude range; d is distribution of AE signals by the duration of pauses; 1, 2, 3 are distributions from the destruction of structural elements of the weld material (1), the normalization zone and the base metal of the welded joint (2), the elements of the weakened welded joint zone (3); $P_u$, $P'_u$, $P''_u$, are probabilities of the amplitude of the AE signal entering the recorded amplitude range $[U_n^a; U^a]$ with a uniform, exponential and with the presence of a maximum in the observed amplitude distribution of AE signals, respectively; $P_{M_t}$, $P_{f_t}$ are the probabilities of signal registration in a given time and frequency range, respectively.
\[
\Theta(t) = \tau_0 \exp\left(\frac{U_0 - \gamma \sigma(t)}{KT}\right)
\]

where \(U_0\) is the activation energy of the destruction process, \(\gamma\) is the activation volume; \(K\) is the Boltzmann constant; \(T\) is the absolute temperature; \(\omega(t) = \gamma \sigma(t) / KT\) is the dimensionless parameter of the strength state of the structural microcell of the material of the object, depending on the structure and time-varying tensile stresses on the microcell \(\sigma(t)\); \(\Psi(\omega)\) is the density distribution function of the parameter \(\omega\) simulating the strength inhomogeneity over the structural elements of the monitored volume \(V\) of the material. Different types of the function \(\Psi(\omega)\) were considered, and in particular:

- log-normal distribution with density function

\[
\Psi(\omega, \mu, \sigma_\omega) = \frac{1}{(2\pi)^{1/2} \sigma_\omega} \exp\left[-\frac{1}{(2\sigma_\omega)^2} (\ln(\omega) - \mu)^2\right]
\]

(3)

- two rectangular with weights of 0.99±0.999 and 0.01±0.001

\[
\Psi(\omega_0, \omega_1, \omega_2) = \begin{cases} 
0.99 / \omega_0, \omega \in [\omega_0, \omega_1 + \omega_2]; \\
0.01 / \omega_2, \omega \in [\omega_0 + \omega_1, \omega_0 + \omega_1 + \omega_2].
\end{cases}
\]

(4)

\(\omega_0, \omega_1, \omega_2\) are the scattering boundaries of the values of the parameter \(\omega\), respectively; \(\sigma_\omega, \mu\) are the parameters of the function \(\Psi(\omega)\).

The ratio of the parameters of the function \(\Psi(\omega)\) included in formulas (3), (4) characterizes the degree of heterogeneity of the strength state of the material, and their change over time is the plastic rearrangement of its structure [18]; parameters (1) \(\tau_0\) and \(U_0\) are the most conservative, determined by the characteristics of the interatomic interaction of the structural element and do not depend on the state of the structure, which gives them a valuable property of universality, which reduces uncertainty when predicting a resource. The values of the parameter \(\gamma \approx 10^{-26} - 10^{-29} \text{ m}^3\) (activation volume) are characteristics of the nanostructure of the material, which is weakly sensitive to its chemical nature. Together with the stresses \(\sigma\), the parameter \(\gamma\) reflects the strength individuality of the structural element.

The integral entering into formula (2) is given the meaning of the probability of recording AE signals coming from an AE source into the range of frequencies \(f\) recorded by the instrumentation, amplitudes \(u\) of AE signals and time intervals \(\Delta t\) (duration of pauses) between them. The type and behavior of the distributions determining the \(F(\Delta t, f, u)\) function are shown in figure 2. Stability (2) determines the conditions of metrological similarity \(C\) and \(\xi\), that is, the metrological homogeneity of the AE control, and the experimental separation of fine disintegration into heterogeneous and homogeneous stages by the kinetic feature from (1) allows selecting an informative fragment of the AE signal flow. The adequacy of the model (1) to the process of microcracking of welded joints is shown in figure 3. The nanometric level of AE fracture monitoring is currently not possible due to the complexity of creating the corresponding microwave AE converter.

The time dependence of the number of impulses of AE at the stage of the most informative homogeneous destruction, recorded, for example, with uniform diagnostic loading of the test object with a constant rate of growth of stress, will have an exponential form:

\[
N_{\text{homog}}(t) = k_{\text{AE}} C_0 KT \exp\left[\frac{(\gamma \sigma t - U_0)}{KT}\right] / (\tau_0 \gamma \sigma)
\]
Figure 3. Assessment of the adequacy of the model. a) Comparison of computer simulation results (solid line) with the results of recording the number of AE pulses (chart points) under loading of overlapping welded joint; b) dependence of the total length of cracks $L_2$ in the weld on the number of loads $N$ for different values of nominal stresses $\sigma$ and the length of the weld $L_w$ (according to [2]); c) comparison of the results of simulation modeling and microscopic study of the time dependence of the concentration of microcracks.
Figure 4. Algorithm for assessing the AE-index of strength $k_{Y_{AE}}$ defect-free welded steel sample type 2, made of steel St3 (a) and the results of the resource assessment of samples of welded joints (b).

The informative concentration-kinetic AE information derived from it, which are free from AEC and therefore are resistant to additive interference and destabilizing factors, are presented in Table. 1. An example of a non-destructive determination of these parameters when loading samples of welded joints is shown in figure 4a, and their relationship with the life and fatigue curve indices for samples of overlap welded joints are shown in figure 4b, figure 1, section 2.3. The values of breaking load, calculated through $k_{Y_{AE}}$ by the formula:

$$F_p = \frac{U_0}{KT} + \ln \left( \frac{C^*}{C_0 F_p k_{Y_{AE}}} \right) / (k_{Y_{AE}})$$

(5)

where $F_p$ is the load growth rate under loading, $C^*/C_0=10^{-2}$, satisfactorily agree with experimentally determined load values corresponding to the moment of crack occurrence with uniform diagnostic loading of samples of welded joints of various types, shapes and sizes with various defects. The average value of the activation energy $U_{0av}$ is 113.6 J/mole, the confidence interval of values (109.7; 117.6) with a probability of 0.99.

According to figure 4, we have:

$X_{AE}=\text{dln}N_{AE}/\text{dt}=0.0271 \text{ s}^{-1}$,

$\text{dF}/\text{dt}=217..38 \text{ N/s}$,
kY_{AE}=X_{AE}(dF/dt)=0.000125 \text{ N}^{-1}

The value of the coefficient \( k \) is determined by the geometric characteristics of the sample cross section or the ratio of the nominal values of the maximum normal stresses in the weld and the load on the sample. With the load on the sample \( F = 1 \text{ N} \), we have \( \sigma = 8225 \text{ Pa} = 0.008225 \text{ MPa} \), therefore

\[
Y_{AE} = \frac{\text{dln}N_{\text{max}}}{\text{d}\sigma} = \frac{\gamma}{\sigma} = \frac{kY_{AE}}{\sigma} = 0.000125 \cdot \frac{1}{0.008225} = 0.015 \text{ MPa}^{-1}
\]

(6)

This value coincides with the value of the parameter \( Y_{R} = \gamma/(KT) \) fatigue curves figure 5a., described by the same expression as \( Y_{AE} \), provided that the fatigue curves are expressed by Zhurkov formula.

Sample activation volume \( \gamma = Y_{AE} \cdot KT = 1.5 \cdot 10^{-8} \cdot 1.38 \cdot 10^{-23} \cdot 300 = 6.21 \cdot 10^{-29} \text{ m}^3 = 6.21 \cdot 10^{-2} \text{ nm}^3 \) has a nano-scale dimension, and is consistent with the values obtained in [18] for AE measurements and deformations.

**Figure 5.** Curves of low-cycle fatigue of welded joints (according to [1]): a - results of low-cycle tests of various zones of defect-free welded joints of steel VMSt3sp (1 is metal of the fillet weld; 2 is metal of the heat-affected zone of the butt joint; 3 is base metal); b - results of low-cycle tests of butt joints of 10HSND steel with a thickness of 20 mm (1 is high-quality connection; 2 is angularity of 8 mm at a length of 1 m; 3 is lack of penetration of 4 mm.); c - illustration of the increase in reliability due to the use of concentration-kinetic indicators \( W_{AE} = W_{R} \) and \( Y_{AE} = Y_{R} \).
Table 1. Multi-model multi-level concentration-kinetic AE-strength indicators, resistant to the effects of interference and destabilizing factors AE control

| AE indicator | Micromodel | Nano model | Macromodel |
|--------------|------------|------------|------------|
| X_{AE}(S^{-1}) | d\ln \xi/dt | \gamma \sigma /KT | " |
| Y_{AE}(Pa^{-1}) | d\ln \xi/d\sigma | \gamma /KT | d\ln N_c/d\sigma^a |
| kY_{AE}(N^{-1})b | d\ln \xi/dF | k\gamma /KT \text{b} | d\ln N_c/dF\text{a} |
| W_{AE} | d\ln \xi/dK_n \text{c} | \omega = \frac{\gamma \sigma}{KT} | lnN_B-lnN_w \text{a} |

\(a\) N_c, N_B, N_w are the slave parameters of the material fatigue curve (figure 3).
\(b\) \(k = \sigma/F\) is the proportionality coefficient between the load \(F\) and the nominal stresses \(\sigma\)
\(c\) \(Kn\) is the load factor (ratio of the diagnostic load to the working one).

The universality of the value of \(N_B\), as cut off by extrapolating the coordinate system of the fatigue curve to the abscissa of the coordinate system (figure 5 b,c), is explained by the stability of the values entering the formula describing the fatigue curve. At constant temperature \(T\) and period \(\tau_{cycle}\) cyclic loading the number of \(N_C\) cycles to failure:

\[ N_C = \frac{\theta}{\tau_{cycle}} = \frac{\tau_0}{\tau_{cycle}} \exp\left[\left(\frac{U_0 - \gamma \sigma}{KT}\right)\right] \]

with \(\sigma = 0\), the value \(N_C = N_B\), where \(\ln N_B = \ln (\tau_0 / \tau_{cycle}) + 0.43U_0 / (KT)\).

Expression mapping \(Y_{AE} = d\ln N_{\Sigma\text{homogeneity}} / d\sigma = \gamma / KT\) and \(Y_R = -d\ln N_C / d\sigma = \gamma / KT\), as well as the numerical values of the \(Y_{AE}\) (6) and \(Y_R\) parameters (figure 5a) reveals their identity \((Y_{AE} = Y_R = 0.015 \text{ MPa}^{-1})\) and suggests the inverse proportionality of the number of \(N_C\) cycles to failure and the number of \(N_\Sigma\) of AE impulses registered at the stage of homogeneous destruction

\[ N_C \approx \frac{A}{N_{\Sigma\text{homog}}} \]

This demonstrates the validity of the hypothesis of linear summation of damages at the stage of homogeneous destruction, which makes it possible to carry out a forecast on the basis of linear extrapolation.

Resource of the control object

\[ N_C \approx N_B/exp W_{AE} \]

A graphical interpretation of the relationship of concentration-kinetic strength indicators with a resource shown in figure 1, section 2.3 and the diagnostic features of the stages of the destruction process and the generalized formulas for resource estimation in Table 2.
Table 2. Diagnostic features of the stages of the destruction process and the resource assessment formulas

| Stage | Stage of destruction | Diagnostic sign of the destruction stage | Resource evaluation formula (T-moment diagnosis) |
|-------|----------------------|------------------------------------------|-----------------------------------------------|
| I     | Delocalized, fine, no heterogeneous | $d^2\xi/dt^2 < 0$ at $\sigma = 0$; $d^3\ln\xi/dt^2 < 0$ at $\sigma = 0$; $dk_{AE}/dt < \omega_2/\omega_0 > 1$; $\sigma > \mu$; DRT = var | $\tau^* = (1 \div 10)T$ |
| I     | Delocalized, fine, heterogeneous | $d^2\xi/dt^2 = 0$ at $\sigma = \text{const}$; $d^3\ln\xi/dt^2 = 0$ at $\sigma = \text{const}$; $dk_{AE}/dt < \omega_2/\omega_0 < 1$; $\sigma < \mu$; DRT = var | Time to localization $\tau^* = f(Y_{AE})$ or $\tau^* = f(W_{AE})$ |
| I     | Localized, fine, no heterogeneous | $d^2\xi/dt^2 < 0$ at $\sigma = 0$; $d^3\ln\xi/dt^2 < 0$ at $\sigma = 0$; $dk_{AE}/dt < 0$ (U/0 < 0); $\omega_2/\omega_0 > 1$; $\sigma > \mu$; DRT = var | $\tau^* = (0,1 \div 0,5)T$ |
| I     | Localized, fine, homogeneous | $d^2\xi/dt^2 = 0$ at $\sigma = \text{const}$; $d^3\ln\xi/dt^2 = 0$ at $\sigma = \text{const}$; $dk_{AE}/dt = 0$; $\omega_2/\omega_0 < 1$; $\sigma < \mu$; DRT = invar | Time before growth $\tau^* = f(Y_{AE})$ or $\tau^* = f(W_{AE})$ |
| II    | Formation and crack growth | $d^2\xi/dt^2 > 0$ at $\sigma = \text{const}$; $d^3\ln\xi/dt^2 > 0$ at $\sigma = \text{const}$; $dk_{AE}/dt > 0$ (U/0 < 0); $\omega_2/\omega_0 > 1$; $\sigma > \mu$; DRT = invar | $\tau^* = (0,01 \div 0,1)T$ |
| II    | Plastic destruction | $d^2\xi/dt^2 < 0$ at $\sigma = \text{const}$; $d^3\ln\xi/dt^2 < 0$ at $\sigma = \text{const}$; $dk_{AE}/dt < 0$ (U/0 < 0); $\omega_2/\omega_0 < 1$; $\sigma < \mu$; DRT = invar | $\tau^* = (0,01 \div 0,1)T$ |

* DRT-difference of arrival times of the AE signal to the AE converter.

Figure 4c shows a graphical illustration of the increase in reliability due to the assessment of concentration-kinetic parameters $W_{AE} = W_R$ and $Y_{AE} = Y_R$.

3. Discussion of results in scientific and applied aspects

Based on a multi-level model of time dependence of AE parameters (1), the information-kinetic approach develops a traditional experimental approach to resource assessment, based on destructive tests of similar working reference samples, construction of fatigue curves and the linear summation hypothesis of damage, differing from it by the type of body samples, the degree of damage to the object and the type of control of their destruction, indicators of strength characteristics, criteria for heterogeneity and strength similarity. The essence of development reduced to the implementation of the following subject-methodical procedures that reduce the uncertainty in the assessment of the resource:

1. The transition from the visual control of the number of cycles to the destruction of standard samples with conditionally identical defects to the automatization of acoustic emission control of the time of destruction of the preset microelements of the material of an industrial object in order to ensure the testability of the damage accumulation process;
2. The transition from the strength characteristics of the strength of standard macro samples to the concentration-kinetic indicators of strength and strength heterogeneity of the material of a technical object, which made it possible to provide informative control;
3. Replacing the spatial-geometric criteria of strength similarity (shapes, sizes, geometric parameters of samples, defects, cracks, etc.) with time (time to failure, parameters of density distribution functions with its associated strength nanocharacteristics), which made it possible to
select AE signals from representative structural elements material through sound filtering of the flow of AE signals from the object of diagnosis by kinetic and statistical features;

4. Identification of parameters of material fatigue curves and time dependencies of AE parameters, which allowed justifying the choice of stable strength characteristics of the material and to ensure the possibility of using the information base of fatigue tests of standard samples.

4. Example of practical use

The practical application of the approach in this paper considered when diagnosing the condition of the outer ring of a rolling bearing. The results of the registration of AE, obtained by its static loading on the stand, presented in figure 6.

For a bearing with a defect grid of 3x3, according to the AE control, we have the number of AE pulses recorded from 145 to 150 seconds equal to 5 and 54, and the change in the diagnostic load during this time occurred at 10,000 N. Then, with the load on the bearing \( R_{\text{work}} = 40,000 \) N we have

\[
W_{\text{AE}} = \ln(54/5)/(1/4) = 9.52
\]

The constant \( N_B \) is calculated from the bearing fatigue curve \((C/P) n = Lh, \text{ppm}\), converted to an exponential form.

One turn the bearing will withstand at a load of \( P = 100 \) C, \( \ln1 = 0 \).

With a load equal to the dynamic load capacity \( P = C \), the number of revolutions of the bearing \( L = 106 \), \( \ln106 = 13.82 \), from the proportions of the exponential fatigue curve \[((100C-C) / C = \ln10^6 / (\lnN_B-\ln10^6)) \] we have

\[
\lnN_B = \ln10^6 (1+1/99)= 13.82 \cdot 1.01 = 13.953
\]

Durability of the bearing in revolutions

\[L=N_B/\exp W_{\text{AE}} = \exp(1.01\ln10^6)/\exp9.52 = \exp(13.953-9.52) = \exp 4.43 = 82,8 \text{ turnover}\]

For \( P_{\text{work}} = 4000 \) H then

\[
W_{\text{AE}} = \ln (54/5)/(1/0.4) = 0.952
\]

Durability in revs

\[L=N_B/\exp W_{\text{AE}}=\exp(1.01\ln10^6)/\exp 0.952 = 425631 \text{ turnover}\]

5. Conclusion

Thus, by the example of welded structures and rolling bearings, the possibility of an effective assessment of their life based on the information-kinetic approach to acoustic emission diagnostics has been shown. As a methodological basis, a multilevel model of temporal dependencies of AE parameters was taken, describing their behavior under conditions of strength and metrological heterogeneity, as a prognostic one, that is, informationally related to the resource and parameters of fatigue curves, the final stage of uniform elastic fine-dispersed destruction is considered heterogeneous material in the form of destruction of representative structural elements. The criteria of metrological and strength similarity arising from the model make it possible to organize the selection of informative AE signals by filtering their flow according to kinetic and statistical features, to justify the choice of valuable multi-level diagnostic AE strength indicators. The proximity of information-kinetic and traditional destructive approaches to resource assessment allows combining the results of AE control with a wide base of accumulated data of fatigue tests, ensuring a reduction of uncertainty in the resource assessment of hazardous technical objects. The effect of applying an approach that allows separating the influence of material of factors of various scale levels (acoustically active and activation volumes) on AE is especially apparent when diagnosing objects exposed to thermochemical effects (hydrogen absorption, corrosion, heat treatment, etc.), when the change in AE activity does not correlates with changes in the degree of danger source [17].
Figure 6. Results of registration of AE rolling bearing. a is the time dependence of the number of AE pulses; b is the amplitude distribution of AE signals; c, d, e, f is appearance and scheme of installation of piezo transducers, g is graphical illustration of the definition of the \( N_0 \) parameter.

References

[1] Makhutov N A, Vorobyev A Z and Gadenin M M 1983 *Structural strength under low-cycle loading* (Moscow: Science) p 271

[2] Makhutov N A, Zatsarinny V V and Bazaras J L 1989 *Statistical laws of small-cycle destruction* (Moscow: Science) p 252
[3] Makhutov N A and Matvienko Y G 2016 Technical diagnostics of residual life and security of technosphere objects Proceedings of the Russian Academy of Sciences and the business program of the “NDT 2016 Territory” forum pp 22-31

[4] Lukyantsev M A, Vildanov R G and Ishkakov R R 2013 Estimation of the residual resource of reservoirs under low-cycle loading Modern problems of science and education 6

[5] RD 26.260.004-91 1992 Methodical instructions. Prediction of the residual life of the equipment to change the parameters of its technical condition during operation (Moscow: Niihimnash) p 50

[6] STO GAZPROM 2-3.5-252-2008 Organization standard. Methods of extending the safe operation of gas pipelines of JSC “GAZPROM” (Moscow: LLC "VNIIGAZ") p 52

[7] Penkin A N, Galstyan L K, Milovanova L N and Penkin N S 2018 Low-cycle fatigue of samples with stress concentrators (Stavropol: Stavropol North Caucasus Federal University) p18

[8] Plotnikov D G, Sokolov S A, Borovkov A I and Mikhailov A A 2015 St. Petersburg state polytechnic university journal of engineering science and technology 1(214) pp 186-193

[9] Badalyan V G, Bazulin E G and Vopilkin A K 2008 Ultrasonic defectometry of metals using holographic methods (Moscow: Mashinostroenie) p 368

[10] Makhutov N A and Razuvayev I V 2017 Integrated remote monitoring of the actual technical condition of FP I and II classes in oil refining, petrochemistry and chemistry using the method and systems of acoustic emission. Problems. Solutions. Results. XXI All-Russian conference on non-destructive testing and technical diagnostics (Moscow: Spectr) p 364

[11] Ivanov V I 2010 The prime problems of acoustic emission diagnostics of technical devices and constructions 10th European conference on non-destructive testing (Moscow)

[12] Ivanov V I 2016 Basic problems and tasks of acoustic emission diagnostics Proceedings of the Russian Academy of Sciences and the business program of the “NDT 2016 Territory” forum (Moscow: Spectr) pp 132-140

[13] Nosov V V 2016 Russian journal of nondestructive testing 52(7) pp 386–399

[14] Nosov V V 2016 Acoustic-emission diagnostics as the basis for improving the strength reliability of machines and equipment Proceedings of the Russian Academy of Sciences and the business program of the “NDT 2016 Territory” forum (Moscow: Spectr) pp 230-243

[15] Petrov V A, Petrov G V and Ryzhov O Y 2005 Comparative analysis of resource definition techniques Proceedings of the St. Petersburg State Polytechnical University 494 8-14

[16] Leksovsky A M, Baskin B L and Yakushev P N 2016 Correlated non-linear interaction of micro / meso defects - a new systemically forming mechanism for the destruction of a heterogeneous system when it is deformed under conditions of constrained deformation The fourth tectonomicrophysical conference at the Institute of Physics of Physics, RAS. Tectonophysics and current issues of Earth sciences (vol 1) ed Rebetsky Y L (Moscow: Institute of Physics of the Earth, Russian Academy of Sciences) pp 282-289

[17] Nosov V V, Makhmuudov H F and Hotchenkov A S 2018 Acoustic emission diagnostics of loss of stability of loaded reinforced concrete beams XXIII St. Petersburg readings on the problems of strength, dedicated to the 100th anniversary of the Physicotechnical Institute named after A.F. Joffe and the 110th birthday of the corresponding member USSR Academy of Sciences A.V. Stepanova (Saint-Petersburg: VVM) p 325

[18] Nosov V V 2017 Russian journal of nondestructive testing 53(5) 368-377

[19] Nosov V V 2014 Russian journal of nondestructive testing 50(12) 719-729

[20] Nosov V V, Nominas S V and Zelensky N A 2015 Peter the great St. Petersburg polytechnic university 2(219) pp 182-190

[21] Nosov V V and Potapov A I 2015 Russian journal of nondestructive testing 51(1) pp 50-58

[22] Nosov V V and Zelensky N A 2017 Russian journal of nondestructive testing 53(2) pp 89-95

[23] Nosov V V, Samigullin G Kh, Yamilova A R and Zelensky N A 2016 Micromechanical model of acoustic emission as a methodological basis for the prediction of welded joints fracture Oil and gas business 14(1) pp 244-253
[24] Bobrov A L, Stepanova L N 2013 Study of the parameters of acoustic emission signals in the control of cast parts of a freight car truck Defektoskopiya 12 pp 61–68
[25] Plotnikov V A and Makarov S V 2010 Activation volume and acoustic emission during high-temperature deformation of aluminum Tomsk state university journal 15(3) pp 1068-71
[26] Ainabekov A I, Raimberdiev T P, Dzhumabaev A A and Eshimbetov Sh T 2006 Engineering calculations of structural elements for durability with low-cycle fatigue, taking into account the influence of temperature Scientific articles Kazakhstan 5 pp 56-61
[27] Buylo S I 2017 Physico-mechanical, statistical and chemical aspects of acoustic emission diagnostics: monograph (Taganrog: Publishing House of the Southern Federal University) pp 184
[28] Leontev A, Aleshin M, Klyavin O and Borovkov A 2018 MATEC web of conferences 148 pp 1–4