Determination of nanocharacteristics of strength of structural materials based on signal recording and simulation of time dependences of acoustic emission parameters

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Abstract. Non-destructive testing of the strength of structural materials and products from them is currently based on the correlation between the strength characteristics of the material in a real object and the results of laboratory tests of the strength of standard macro samples. The strength properties and conditions of control’s heterogeneity of different material’s zones of a complex real object make this correlation ambiguous, introducing uncertainty in the results of control. The solution of the problem is connected with the necessity of information transfer to the micro-and nano-level control that determines the strength, the universal physical nanoconstants and the applying of representative micro structural elements of the material as reference. The selection’s principles of these elements and the method of assessing their strength characteristics are considered on the basis of information filtering the results of recording acoustic emission signals (AE) and the micro mechanical model of its parameters.

Introduction

Non-destructive testing of the strength prediction of the resource of structural materials and products from them is related to the solution of industrial safety ensuring issues and should be based on the development of methods for long-term mechanical destruction’s prediction that allows for the adoption of risk-reducing preventive actions. Special features of damage prediction are assigned to diagnostic methods based on the registration of acoustic emission signals \cite{1, 2}. During the solving the problem of long-term prediction of the residual lifetime of materials and structures, there are two main problems with the application of standard techniques for strength AE control:

1. Low learning ability of the statistical approach due to the low degree of universality of the used statistical invariants and standards and as a consequence the low information content of the used statistical models. Trainees on “imperfect” standards, techniques work poorly on examples not participating in the training.

2. Low noise immunity of methods due to poor filtering of recorded signals, instability of correlations and incorrect formulation and solution of inverse problems of state recognition.

The development of AE strength control technologies should be limited to:

- operational aspect’s comprehensive formulation of ensuring the efficiency of industrial facilities;
the allocation of strength as the main criterion for their efficiency;
• modeling of determining the strength and residual life of the damage accumulation’s process, limited by the moment of achieving critical damage;
• ensuring the possibility of predicting that moment based on of correct observation of the damage accumulation process using the AE method.
Reducing the destabilizing effect of interference, uncertainty in the results’ interpretation of signal registration and the connection of the criteria for the activity of AE sources with the efficiency criteria for complexly loaded objects is possible based on the principles of informational optimization of AE controls.

Method
The primary AE recorded during the tests is quantitatively described by the micromechanical model of time dependencies of the AE parameters, built on the basis of fine modelling of the longest first stage of destruction, the laws of the kinetic theory of strength and analysis of the results of recording elastic radiation.

To ensure the information nature of the AE control, the values of the primary parameters of the AE should have a meaning of analogues of the material damageability and, in particular, be proportional to the concentration C(t) of the resulting micro cracks.

\[
N_\xi(t) = V \iiint_{\Delta t,f,u} \Phi(\Delta t, f, u) \, du \, df \, d\Delta t \, C_0 \, \mu \, F(x) \, \Psi(\omega) \left[ 1 - \exp \left[ -\int_0^1 dt' / \theta(U_0, \omega(t')) \right] \right] \, d\omega, \quad (1)
\]

where \( \theta(U_0, \omega(t')) = \tau_0 \exp \left[ \left( U_0 - \gamma \sigma(t') \right) / (KT) \right] \) is Zhurkov’s formula.

Every parameter of the model (1) has its specific physical nature and depends on distinct factors what allow to reveal mechanisms of impact of these factors on material’s features:

• parameter \( V \iiint_{\Delta t,f,u} \Phi(\Delta t, f, u) \, du \, df \, d\Delta t \, C_0 \), where \( V \) is controlled volume of material, \( \Phi(\Delta t,f,u) \) is AE signals’ density function of pauses’ duration \( \Delta t \), frequency \( f \) and amplitude \( u \), \( C_0 \) is structural elements concentration in material, characterizes amount of AE sources which are literally structural elements which can be “heard” via AE equipment during the process of destruction;
• parameter \( U_0 \) (activation energy of destruction process of molecular links) doesn’t depend on state of material structure and is defined through characteristics of interatomic interaction (chemical ties) of structural element;
• parameter \( \omega = \gamma \sigma / KT \) is parameter, characterizing decrease of activation energy of destruction process, and being a strength characteristic of structural microelements;
• parameter \( \gamma \) (activation volume) is characteristic of molecular nanostructure of material. Parameters \( \gamma \) and \( \omega \) are faintly sensitive parameter to its chemical nature;
• correspondence of the variables of \( \Psi(\omega) \) function characterizes the degree of inhomogeneity of material’s mechanical state at a molecular level.

There are could be used the following types of function modeling \( \Psi(\omega) \):

• logarithmic-normal allocation:

\[
\Psi(\omega, \mu, \sigma_3) = \frac{1}{\sqrt{2\pi}\sigma_3\omega} \exp \left[ -\frac{1}{2\sigma_3^2} \left( \ln(\omega) - \mu \right)^2 \right], \quad (2)
\]

where \( \mu, \sigma_3 \) are parameters of allocation;
• two-rectangular with scales 0,99±0,999 and 0,01±0,001:

\[
\Psi(\omega, \omega_0, \omega_1, \omega_2) = \begin{cases} 0,99 / \omega_1, & \omega \in [\omega_0, \omega_0 + \omega_1]; \\ 0,01 / \omega_2, & \omega \in (\omega_0 + \omega_1, \omega_0 + \omega_1 + \omega_2] \\ \end{cases}; \quad (3)
\]
• limited Weibull distribution with the parameters \( k, \lambda, \) and \( q, \)

\[
\Psi(\gamma) = \begin{cases} A \cdot \left( k / \lambda \right) \cdot \left( \gamma / \lambda \right)^{k-1} \exp \left( -\left( \gamma / \lambda \right)^k \right), & \gamma \in [0, q), \\ 0, & \gamma \in [q, \infty), \end{cases} \quad (4)
\]
where \( A = \frac{1}{\int_q^{\infty} \left( \frac{k}{\lambda} \right)^{k-1} \exp \left( -\frac{k}{\lambda} y \right) dy} \).

where \( A \) – normalization factor; \( k, \lambda, q \) – distribution parameters.

The value of the parameter \( \gamma \) that was obtained for the uniform destruction region was taken as the initial parameter for the start of the iteration procedure of selecting the parameter \( \lambda \) value. The coefficient \( k \) value was specified to be equal to 3, which best corresponded to the shapes of the size distributions of actual flaws in weld seams. The point of the survey lay in defining of systematical variability of the parameters within changes of distinct technological and exploitation factors and was based on possibility of operational evaluation of these parameters due to results of acoustic emission tests.

Different samples of heterogeneous materials were exposed to destructive AE tests in regimen of steady loading with constant speed of tension rise. It was noticed during the tests that the view of timing dependences \( N_\Sigma (t) \) was affected by such factors as size of filling material particles, time of isolation of the samples after their manufacturing, heat treatment and chemical saturation of uppermost layers, what can be explained by changing of degree of structural inhomogeneity of materials.

In the vast majority of cases timing dependences on number of AE impulses have a view of exponents, aligning in half-logarithmic coordinates (figure 1).

![Figure 1](image)

**Figure 1.** Timing dependences of total number of AE signals \( N_\Sigma \) registered from the start of steady loading of samples of composite materials.

Defining of parameters included in (1) was carried out by solving of the following system:

\[
\begin{align*}
U_0 &= \sigma_{d} X_{AE} KT / \sigma + KT \left( 35 - \ln \left( X_{AE} \right) \right) = KT \left( \sigma Y_{AE} + 35 - \ln \left( \dot{\sigma} Y_{AE} \right) \right) \\
\gamma &= X_{AE} KT / \sigma = KT \cdot Y_{AE} \\
\ln \left( k_{AE} C_0 \right) &= \frac{U_0}{KT} + \ln \left( N_\Sigma + \ln \left( \tau_0 X_{AE} \right) \right) 
\end{align*}
\]

(5)

where \( \sigma_{d} \) is strength limit of a sample, \( \dot{\sigma} \) is speed of tension’s growth in the sample during the time when the sample was steady loaded.

After calculations of the system (5) which were carried out via special software (figure 2-3) there were constructed tables and charts with every dot corresponding to 6 to 7 tests. Research results allowed to formulate mechanisms of impact of distinct technological and exploitation factors on material strength and to optimize manufacture technologies and algorithms of non-destructive control.
Figure 2. Automated determination of function’s parameters $\psi(\omega) \rightarrow \psi(\gamma)$ of the kinetic AE model.

Figure 3. Determination of parameters of kinetic AE model: a) determination of the angular coefficient $X_{AE}$ of dependence’s linear range of number of AE impulses’ logarithm in relation to time. For the tested sample: $X_{AE} = 0.017 \, \text{c}^{-1}$; b) the distribution of the $\gamma$-parameter and $\gamma$ found from the angular coefficient $X_{AE}$ at linear range of dependence.
The micromechanical destruction model of the material divides the first stage of the finely dispersed destruction of the material into homogeneous and heterogeneous destruction stages that conforms the two-stage separation of dissipative properties [8]. During the heterogeneous stage, the least durable elements of the material are subjected to destruction; these elements are destroyed after the first loading and due to their small quantity are completely eliminated from the process of destruction. Homogeneous destruction is less intense, however, after the termination of the heterogeneous stage begins to dominate.

In table 1 the connection between the state of the material structure and some types of strength heterogeneity and stages of destruction and their acoustic emission diagnostic signs is considered.

**Table 1.** The relations of the material’s structure condition with the types of strength heterogeneity, stages of destruction and diagnostic AE signs of these stages

| Structure state | Stages of destruction | Types of strength heterogeneity | Diagnostic AE signs |
|-----------------|-----------------------|---------------------------------|---------------------|
| Destructive (weak) | Delocalized fine inhomogeneous | ++<sup>a</sup> ++ ++ | Fall of AE activity and AE amplitude before final destruction, DRT<sup>d</sup> variation, Kaiser effect |
|                  | Delocalized fine inhomogeneous | +<sup>b</sup> + + | Drop of activity, amplitude of AE, variation of DRT<sup>d</sup>, Kaiser effect |
| Without hub      | Delocalized fine homogeneous | +<sup>c</sup> - - | DRT variations, the Felicity effect, the ability to assess the concentration-kinetic strength AE parameters |
|                  | Localized fine inhomogeneous | - + + | Drop in activity, AE amplitudes, DRT<sup>d</sup> invariant, Kaiser effect |
| With hub         | Localized fine homogeneous | - - - | Invariant DRT<sup>d</sup>, the Felicity effect, the ability to assess the concentration-kinetic strength AE indicators |
| Hub Development  | Crack formation and growth | - + + | Increasing the spread of amplitudes, duration of pauses, the ability to assess the concentration-kinetic strength AE parameters, the Elber effect |
|                  | Plastic destruction      | - - + | Invariant DRT<sup>d</sup>, increase overlap ratio |

<sup>a</sup> «++» - increased heterogeneity;
<sup>b</sup> «+» - a significant heterogeneity;
<sup>c</sup> «-» - insignificant heterogeneity;
<sup>d</sup> DRT is the difference between the arrival times of AE signals on the registration channels.

Defective samples have short or absent area of kinetically heterogeneous destruction. The amplitudes of the AE signals increase after the excess of the initial loading. This effect is interpreted as a demonstration of the scale effect: large structural elements are less durable and collapse after the first loading and the destruction of the remaining smaller elements is accompanied by the transfer of less energy. A further increase of amplitude is also associated with an increase of stresses where smaller but more durable structural elements are also destroyed. The behaviour of the AE parameters of reloading samples patterned with these positions with idealized variants of the fracture process is shown in figure 4.
Real material is destroyed under time-depnd strength heterogeneity. The degree of heterogeneity gives the information about the condition of the object: the course of the process of kinetically heterogeneous destruction indicates a safe state of the object and the course of the process of homogeneous destruction, in contrast, indicates the presence and development of a dangerous defect. It is possible to estimate this degree based on the basis of imitation computer simulation determining the value of the ratio of the parameters of the function $\Psi(\omega)$.

The physical meaning of these ratios of the parameters of the function $\Psi(\omega)$ is also revealed by comparing with other indicators of heterogeneity and in particular, according to the results of experimental data processing obtained during AE testing of welded samples of various degrees of surface layer processing where most of the geometrically heterogeneous elements are located. In particular, there was a good correlation of the ratio $\omega_2/\omega_1$ with the removed surface area of the overlap welds (figure 5 a-e, table 1) and ring welded samples (figure 5e, table 2). The results of the study indicate the connection between the parameters of the function $\Psi(\omega)$ and the area of the most structurally inhomogeneous region of samples of welded joints.

Figure 4. Behaviour of AE parameters of a reloading material with idealized variants of kinetically heterogeneous (1) and homogeneous (2) destruction.

Figure 5. Test samples with different shapes, types of loading and degree of imperfection: a) butt and b), c), d) -lap-welded joints 1- sample, 2-weld, 3-top grip loading device, 4-bottom grip loading device, 5-thumb, 6- Sensors of AE; e) ring welded samples
Table 2. Correlation of the ratio of the parameters of the distribution density function $\psi(\omega)$ with the area of $\psi(\omega)$ the removed surface of the samples of overlap welded joints (figure 5 b, c, d)

| Sample type                | No sample | Defect type   | Sample type, mm$^2$ | $\omega_2/\omega_1$ |
|----------------------------|-----------|---------------|---------------------|---------------------|
| Front weld                 | 1         | -             | 0.000               | 2.833               |
|                            | 2         | 2 holes d6    | 56,520              | 3.000               |
|                            | 3         | 4 holes d6    | 113,040             | 24.000              |
|                            | 4         | 1 holes d6    | 28,260              | 4.667               |
| Front weld and 2 flank welds | 5         | -             | 0.000               | 3.938               |
|                            | 6         | 6 holes d6    | 169,560             | 31.429              |
|                            | 7         | 12 holes d6   | 339,120             | 242.857             |
|                            | 8         | 3 holes d6    | 84,780              | 66,667              |
|                            | 9         | 3 holes d6    | 84,780              | 10,667              |

The correlation coefficient of the ratio $\omega_2/\omega_1$ with the area of defects 0.918

Table 3. Correlation of the ratio of the parameters of the density distribution function $\psi(\omega)$ of ring samples (figure 5 e)

| № sample | Sample’s defects | $\sigma_3/\mu$ | $\omega_2/\omega_1$ | $\omega_1/\omega_0$ | area A surface removed thermally untreated foot weld, mm$^2$ | Maximum stress near defects $\sigma_{\text{max}}, \text{MPa}$ |
|----------|------------------|----------------|---------------------|---------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| 5        | 2 non-through holes inside: Ø4 and Ø3 mm; 2 non-through holes outside: Ø2.4 and Ø3.2 mm; fistula 1 mm | 0.92 | 0.875 | 0.89 | 19.6 | 268 |
| 4        | 2 through holes Ø4 (burrs) | 2.1 | 4.1 | 2.2 | 9.48 | 247 |
| 1        | 2 through holes Ø4 (burrs) | 3.56 | 6.45 | 3.1 | 25 | 259 |
| 3        | 2 non-through holes; inside Ø3.5 mm and outside Ø3 mm | 3.375 | 6 | 2 | 16.7 | 266 |
| 2        | without defects | 12 | 14.29 | 9.3 | 0 | 188 |
| Correlation coefficient with $\sigma_{\text{max}}$ values | -0.95 | -0.89 | -0.97 |
| The correlation coefficient with the values A | -0.75 | -0.68 | -0.76 |

According to the table 3, the correlation of ratios $\sigma_3/\mu$, $\omega_1/\omega_0$, $\omega_2/\omega_1$ with the values of the area of thermally untreated seams and maximum stresses is rather high which indicates the self-descriptiveness of the presented parameters. Thus, the fact of registration of non-uniform destruction is informative and indicates a safe state of the object. In this case, the estimation of the state of the object takes place at the stage of primary loading which allows reducing the resource and time costs during its study.

Determining the parameters of the model is the most difficult because it is the most abstracted and requires in detail a reasonable acceptance of additional conditions that remove unnecessary uncertainty. The greatest number of papers in one form or another is devoted to finding the connection...
between the parameters in (1) based on the solution of the dynamic problem of the theory of elasticity. The search is complicated when taking into account the anisotropy of elastic properties, leading to uncertainty in the value of the coefficient $k_{AE}C_0$, reflecting the individuality of the results of AE measurements and dependence on the type of object being diagnosed, its shape, size, type of defects, manufacturing technology, type of direct state, equipment, interference, the method and quality of mounting sensors, the gain of the measuring path of the AE system and its oscillations, the distance of the sensor to the AE source and other factors destabilizing the relationship of the AE parameters to the degree of the danger defect or strength characteristics of the object of control.

To reduce the degree of influence of these factors, the stabilizing values of the $k_{AE}$ conditions of the AE measurements are formulated, which consist in ensuring at the time of the AE control of:

- the stability of the controlled volume of the diagnosed object;
- the stability of the gain and the thresholds of discrimination of the measuring system of AE;
- the stability of the characteristics of the energy or amplitude distribution of AE signals;
- the similarity of diagnostic and working loading of the diagnosed object;
- the constant speed of the diagnostic loading.

The approach to the processing of primary AE information makes it possible to formulate the energy, structural and time-dependent characteristics of strength according to micro and nano-levels, to propose a number of valuable diagnostic AE parameter of the strength condition (Table 4, [3–10]) based on algorithms for non-destructive AE strength control.

| AE-indicator | Micro-model $X_{AE}$ | Nano-model $Y_{AE}$ | Macro-model $k_{AE}$ | Dimension |
|--------------|-----------------------|---------------------|-----------------------|-----------|
| $X_{AE}$     | $d\ln \xi / dt$      | $\gamma \sigma / KT$ | $-\ln N_c / d\sigma$ | $Pa^{-1}$ |
| $Y_{AE}$     | $d\ln \xi / d\sigma$ | $\gamma / KT$       | $d\ln N_c / d\sigma$ | $Pa^{-1}$ |
| $kY_{AE}$    | $d\ln \xi / dF$       | $k\gamma / KT$      | $d\ln N_c / dF$      | $N^{-1}$  |
| $W_{AE}$     | $d\ln \omega / dKH$  | $\omega = \gamma \sigma / KT$ | $\ln N_B - \ln N_{working}$ | $-\ln$ |

where $\xi$ is the primary parameter AE, $d\sigma$ is the stress growth rate in the material, $A_0 = k_{AE}C_0 / \tau_0 \exp[(U_0 - \gamma \sigma(t))/\gamma KT]$; $K_H$ is the load factor (the ratio of the diagnostic load to the working load), $k=\sigma / F$ is the proportionality coefficient between the load and the nominal voltage, $N_c$, $N_B$, $N_{working}$ -parameters of the material fatigue curve.

Experimental section.

To solve the problem, the method of express control of strength materials has been developed, aimed at determining the resource-related parameters of the damage accumulation process in welded joints by means of rapid assessment of concentration-kinetic acoustic-emission strength indicators (figure 1, 2). The stage of fine destruction is divided into stages of non-uniform and uniform destruction. The number of impulses $N_{AE}$ AE recorded at loading with a constant rate of stress growth at the stage of predictive uniform fracture is described by the time dependence

$$N_{AE}(t) = k_{AE}C_0 KT \exp \left[ \frac{(\gamma \sigma - U_0)}{(\gamma KT)} \right] / (\tau_0 \gamma \sigma)$$

and at the same time

$$\frac{d\ln N_{AE}(t)}{\sigma dt} = \frac{Y_{AE}}{kT} = Y_{AE}$$

Table 4. Models of the most valuable AE-indicators of the strength state of technical objects and their dimensions

| AE-indicator | Micro-model $X_{AE}$ | Nano-model $Y_{AE}$ | Macro-model $k_{AE}$ | Dimension |
|--------------|-----------------------|---------------------|-----------------------|-----------|
| $X_{AE}$     | $d\ln \xi / dt$      | $\gamma \sigma / KT$ | $-\ln N_c / d\sigma$ | $Pa^{-1}$ |
| $Y_{AE}$     | $d\ln \xi / d\sigma$ | $\gamma / KT$       | $d\ln N_c / d\sigma$ | $Pa^{-1}$ |
| $kY_{AE}$    | $d\ln \xi / dF$       | $k\gamma / KT$      | $d\ln N_c / dF$      | $N^{-1}$  |
| $W_{AE}$     | $d\ln \omega / dKH$  | $\omega = \gamma \sigma / KT$ | $\ln N_B - \ln N_{working}$ | $-\ln$ |
Figure 6. Graphic interpretation of the connection parameters of $W_{AE}$ and $Y_{AE}$ with the resource $N_C$. $\sigma_{R}$, $\sigma_{RD}$ – limit of endurance of the standard and the real part, respectively, $\sigma_{working}$, $\sigma_{c}$ – working and critical stresses.

Figure 7. Experimental estimate of AE strength parameters, $X_{AE}$, $Y_{AE}$, $W_{AE}$ complexly loaded structures (on the example of a defect-free sample of overlapped welded joint of steel).

Figure 8. Low cycle fatigue curves: a – results of low-cycle test of different zones of faultless tie-in welds of steel (1 – metal of corner weld; 2 – butt joint heat affected metal; 3 – base metal); b – results of low-cycle tests of butt joints of steel with a thickness of 20 mm (1 – quality connection; 2 – angularity of 8 mm at a length of 1 m; 3 – lack of penetration 4 mm)

The universality of the value of $N_B$ at a constant temperature and loading frequency is justified by the connection with stable quantities that are included in the equation of the fatigue curve, expressed by the Zhurkov formula, when

$$N_C = \frac{\theta}{\tau_{cycle}}, \quad (8)$$

$$\log N_B = \log\left(\frac{\tau_0}{\tau_{cycle}}\right) + 0.43U_0/(KT), \quad (9)$$

where $\tau_{cycle}$ is the cycle period.

Comparison of the forms $Y_{AE} = d\ln N_C / d\sigma = \gamma / KT$ and $Y_R = d\ln N_C / d\sigma = -\gamma / KT$ and the values of these parameters obtained in figures 7 and 8 reveals their identity, suggests the inverse proportionality of the number of $N_C$ cycles to destruction and the number of $N_B$ registered impulses of AE which illustrates the validity of the hypothesis of linear summation of damages, which is actively used in the practice of designing engineering objects of mechanical engineering.

**Conclusion**

1. The characteristics of strength, parameters of the process of destruction and AE materials depend on the result of competition simultaneously occurring in the material processes of destruction and plastic deformation of structural elements.
2. The resource of the majority of long-loaded materials, structures and structures is determined by the process of micro cracks formation, occurring in conditions of elastic deformation.

3. The destruction consists of following stages:
- finely dispersed (scattered over the volume of the object or locally grouped in the defect area) accumulation of the concentration of micro cracks, consisting of kinetically inhomogeneous and homogeneous stages;
- integrated localized discontinuity (formation or growth of a crack), flowing elastically or plastically.

4. Acoustic emission of elastically deformed materials is associated mainly with the process of micro cracks formation. The number of signals from plastic deformation of overstressed structural elements is relatively small. To reduce their destabilizing effect on the results of resource prediction, information filtering of signals should be applied with selection of signals corresponding to the destruction of the most durable structural elements that determine the resource.

5. The usage of the micromechanical model of the destruction process and the acoustic emission parameters reflecting its temporal parameters allows us to propose a mathematical model of the strength heterogeneity, its quantitative criteria and a method for their evaluation, remove uncertainty in recognizing the state of monitored inhomogeneous objects, reveal the information content of the Kaiser effect and other signs of heterogeneous destruction.

6. Comparison of the parameters of the mathematical model describing the time dependence of the number of AE pulses and the parameters of the fatigue curve of samples of structural materials reveals their identity and confirms the hypothesis of linear summation of damage accumulated in the material at the stage of uniform destruction.

References

[1] Petrov V A, Bashkarjov A Y, Vettegren V I 1993 The physical basis of forecasting of structural long-lasting materials (Saint-Petersburg: Politehnika) p 475

[2] Ivanov V I 2010 The prime problems of acoustic emission diagnostics of technical devices and constructions (Moscow:10th European Conf. of Non-Destructive Testing)

[3] Nosov V V 2014 Russian Journal of Nondestructive Testing 50(12) pp 719–29

[4] Nosov V V, Potapov A I 2015 Russian Journal of Nondestructive Testing, 51(1) pp 50–58

[5] Nosov V V 2016 Russian Journal of Nondestructive Testing 52(7) pp 386–99

[6] Nosov V V 2017 Russian Journal of Nondestructive Testing 53(5) pp 368–77

[7] Nosov V V, Zelenskii N A. 2017 Russian Journal of Nondestructive Testing 53(2) pp 89–95

[8] Tsenev A N, Akimova E V. 2017 IOP Conf. Series: Earth and Environmental Science 87

[9] Leontev A, Aleshin M, Klyavin O, Borovkov A 2018 MATEC Web of Conferences 148 pp 1–4

[10] Plotnikov D G, Sokolov S A, Borovikov A I, Mikhailov A A 2015 St. Petersburg State Polytechnic University Journal of Engineering Science and Technology 1(214) pp 186-93