Application of the acoustic emission method in problems of vehicle diagnostics

S I Builo1,2, B I Builo3, V I Kolesnikov1, V D Vereskun1 and O N Popov1

1 Rostov State Transport University, Rostov-on-Don, 344038 Russia
2 Vorovich Institute of Mathematics, Mechanics and Computer Science, Southern Federal University, Rostov-on-Don, 344090 Russia
3 Russian University of Transport (MIIT), Moscow, 127994 Russia
sibuilo@yandex.ru

Abstract. The report is devoted to the results of acoustic emission (AE) diagnostics of vehicles obtained by the Rostov school of AE over the past 45 years. Over the years, we have carried out a series of studies both on the AE itself and on its practical application for the diagnosis of mission-critical products, including objects of aviation and rocket and space transport. The fundamentally new interdisciplinary approach proposed by us, which consists in using the kinetic concept of strength, the Poisson model of the defect formation process, and the experimentally discovered physical and mechanical features of the AE phenomenon (including the statistical parameters of the random AE process that are stable due to a number of limit theorems) is described. Practical application of the obtained results is shown on the examples of AE diagnostics of the strength of structural elements of the Russian heavy transport helicopter and the Russian Shuttle Buran.

1. Introduction
Rostov State (now Southern Federal) University was one of the first organizations in the USSR, where from the beginning of the 1970s, under the leadership of Academician of the Russian Academy of Sciences I I Vorovich, the research studies on the diagnosis of mission-critical products have been conducted, including products of aviation and rocket and space technology. Currently, the AE method is being actively developed at the Rostov State University of Railway Engineering under the supervision of Academician of the Russian Academy of Sciences V I Kolesnikov, as part of the development of new methods for diagnosing aviation and railway transport objects.

The AE method has been actively developed since the late 1960s [1]. However, the practical application of the AE method is hindered by the constant distortion and overlapping of real signals during their multimode propagation in a solid, which makes it very difficult, and in many cases impossible to solve the inverse problem of quantitative restoration of the parameters of structural changes in materials from the recorded AE signals [2].

2. Methods, results and discussion
We propose and develop a fundamentally new interdisciplinary approach, which consists in using the kinetic concept of strength, the Poisson stream model of the defect formation process, and the experimentally discovered physical and mechanical features of the AE phenomenon (including the statistical parameters of the random AE process that are stable due to a number of limit theorems). This approach allows you to restore the stream of damage inside the body according to the parameters
of AE signals recorded on its surface and *up to several times* (with a strong AE distortion) *increases the reliability of diagnostic results*.

The essence of the recovery method is to determine the required characteristics of the process under study by the densities (or distribution functions) of these parameters, which general form is established on the base of the physical nature of the AE effect [2]. In this case, the parameters of a specific distribution are estimated from the pulses that have not yet overlapped, and then the distribution is extrapolated to the area of strong distortion and overlap of the received emission signals. The recovery algorithms that are optimal for varying degrees of distortion and overlap of AE signals recorded on the surface of the body are obtained.

For the case of registering the detected AE signals and the average degree of distortion and overlap, the resulting recovery formula for \( \hat{N}_a \) is the stream intensity (the number of AE acts or events per unit of time) that has the simplest form [2]:

\[
\hat{N}_a = \hat{N}_r \exp \left[ \frac{\Sigma t_0}{T - \Sigma t_0} \right]
\]

where: \( \hat{N}_r \) is the intensity of the stream (so-called AE activity) of the detected AE signals on the surface of the body; \( \Sigma t_0 \) is the total duration of the AE signals at the output of the recording path for the intensity measurement interval \( T \) (for example, \( T=1s \) or \( T=0.1s \)).

### 2.1. AE diagnostics of thermal protection elements of the orbital space aircraft “Buran”

The practical use of the obtained results is confirmed by the example of diagnostics of thermal protection elements of the first Russian orbital space aircraft “Buran”. The most vulnerable element of reusable spaceships (shuttles) is their thermal protection.

**Figure 1.** The “Energiya-Buran” system at the start. Photo autographed by the Chief Designer of Buran Gleb Lozino-Lozinsky.

**Figure 2.** AE diagnostics of the strength of space thermal protection elements of Buran aircraft: \( P \) – the applied load; 1 – aircraft skin; 2 – thermal insulating tiles; 3 – AE transducer; 4 – AE diagnostic complex AP-71E; 5 – computer.
A tragic confirmation of this was the death of the first American reusable space shuttle “Columbia” along with all seven members of its crew in 2003 due to damage to the thermal protection of the lower left wing. For the first time, NASA encountered serious damage to thermal protection back in 1998 during the third flight of the shuttle “Atlantis”. Its thermal protection was broken by fragments of the front cone of the right solid fuel accelerator damaged at the start, and as a result more than 700 thermal protection tiles were partially damaged.

When landing on the Earth, the ship was saved only by the fact that there was a flat steel part of telecommunication equipment under the fallen-off thermal protection tiles in the most heated part of the ship’s bottom instead of aluminum sheathing.

As you know, in our country a similar first domestic reusable transport orbital spaceship “Buran” was also created and made a successful flight into space (Figures 1, 3 (a)).

When a space shuttle enters the dense atmosphere during its return to Earth, its speed is 10-20 times higher than the speed of a bullet, so that when braking in the Earth’s atmosphere, structural elements are heated to a temperature of more than a thousand degrees!

The management of the company “Molniya” that built Buran invited us to participate in joint work on the development of methods and equipment for AE diagnostics of the strength of its thermal protection elements. Extremely stringent requirements are imposed on the reliability of thermal protection tiles, and the AE method was supposed to be used in addition to other known methods to further increase the reliability of the results of their control and diagnostics.

A simplified block diagram of the AE method we developed for diagnosing the thermal protection of Buran is shown in Figure 2. Elements of heat protection, for example, in the form of tiles glued to the fuselage, were mechanically loaded to tear off using the applied load P. AE transducer was installed on the surface of the diagnosed tile inside the loading device, which transmitted signals through the preamplifier to the input of the digital AE of the diagnostic complex AP-71E developed by us.

For several years, we were able to improve the method and develop a model of the diagnostic complex AP-71E, which the AE records of the tiles were later used to develop methods for assessing the damage stream from the restored parameters of the stream of AE events.

As an example, Figure 3b shows the results of the restoration of the damage stream obtained by us when loading one of the tiles. The restoration of the stream of AE events was carried out according to the formula (1). It can be seen that AE signals appear long before its destruction, and an increase close to the exponential law of the intensity of the restored stream of AE events, $\dot{N}_a$ is in good agreement with the model of exponential accumulation of damage before destruction [2]:

$$C = C_0 \exp(\gamma(\varepsilon - \varepsilon_a));$$

$$\dot{N}_a, \text{s}^{-1}$$

Figure 3. The reusable Buran spacecraft in flight (a) and AE diagnostics of one of its black thermal protection tiles (b). Cross shows the moments of destruction.
where \( C_0 \) is the initial concentration of damage; \( \gamma \) is constant breeding; \( \varepsilon_* \) is deformation of the beginning of damage accumulation; \( \varepsilon \) is current deformation. \( C_0, \gamma, \) and \( \varepsilon_* \) are quantified according to AE tests [2].

The obtained results allowed us by using the AE signals to quantify the initial concentration and constant multiplication of microdefects in the tile material. This information, necessary for the diagnosis of the pre-destructive state and the assessment of the criterion of destruction, can be hardly obtained by any other physical research methods.

### 2.2. AE diagnostics of hydrogen embrittlement of materials

We also obtained interesting results on AE diagnostics of hydrogen embrittlement of materials. Already now, all the engines of vehicles, in principle, can be converted to hydrogen instead of kerosene and gasoline, however, if special measures are not taken to reduce hydrogen embrittlement, then all aircrafts will fall, and after a while, cars will surely “fly into the air”! Figure 4 shows our results on AE selection of nickel alloys for hydrogen-oxygen rocket engines RD-0120. These engines developed by KBKhA (Design Bureau “Khimavtomatiki” founded by Kosberg) operate on the most efficient oxygen-hydrogen fuel (fuel is liquid hydrogen at \(-255^\circ C\), oxidizer is liquid oxygen at \(-186^\circ C\)). Four of these engines were installed on the central block of the carrier rocket “Energiya” (Figure 1).

With the help of specialists from other organizations, KBKhA designers conducted extensive studies of the performance of structural materials in hydrogen at low, room and elevated temperatures, at various pressure levels and strain rates, which made it possible to establish patterns of reduction in the properties of steels and nickel alloys from hydrogen embrittlement.

![Figure 4](image)

**Figure 4.** Hydrogen-oxygen rocket engines RD-0120 (a) and diagnostics of hydrogen embrittlement of nickel alloys (b): 1 – normal; 2 – hydrogen resistant alloy. Crosses show moments of destruction.

Figure 4 (b) shows some of the results of the effect of hydrogen on the mechanical and acoustic emission characteristics of nickel alloys in a gaseous hydrogen medium in the temperature and pressure range. The restoration of the stream of AE events was carried out according to the formula (1). The Figure shows the results at constant pressure and room temperature that we obtained together with employees of the Bureau of Non-Destructive Testing of the department of the main metallurgist of KBKhA and Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine.
It can be seen (Figure 4 (b)) that alloys with different hydrogen resistance strongly differ in the intensity of the stream of the AE events $N_a$ at low-cycle fatigue, which allowed us to propose a *method for assessing the hydrogen resistance of materials* by AE parameters.

It has been established that for alloys with low hydrogen resistance, an increase in hydrogen pressure enhances its effect on strength and is accompanied by an increase in the intensity of the stream of AE events. A significant increase in temperature practically restores the initial fatigue strength and is accompanied by a significant decrease in the stream of AE events.

The effect of hydrogen at the initial stages of loading can be interpreted as an additional blocking of dislocations by impurity atoms (hydrogen), leading to a decrease in ductility and, as a consequence, earlier formation of microcracks. With a further increase in the load, hydrogen embrittlement is already possible due to intergranular “wedging” of the material under the pressure of hydrogen diffusing to the grain and block boundaries, as well as transported by dislocations moving under the action of the applied stress. High temperature worsens the conditions for dislocation blocking by hydrogen atoms, suppressing its effect on strength and AE, which we established experimentally.

### 2.3. AE diagnostics of railway and helicopter structures

The AE method has recently found more and more application in solving the problems of diagnostics of *railway transport* products, however, so far mainly to control cracks and determine the coordinates of growing defects in cast structures [3,4]. We are conducting research on the creation of methods for diagnosing friction of a wheel-rail pair with a special coating that increases its durability due to a significant reduction in friction [5]. Currently in trial operation there is a lubrication system based on the creation of a new multilayer antifriction nanomodified coating on the side of the rail.

Figure 5 shows our results on AE diagnostics of the stages of destruction of this fundamentally new anti-friction coating for a pair of “wheel-rail”. The restoration of the stream of AE events was carried out according to the formula (1). It can be seen that there are 3 stages of destruction and a strong correlation of the friction coefficient with the stream of AE events is observed. *This allows an express assessment of the coefficient of friction according to AE tests even without direct measurement of this coefficient*. Let us demonstrate it.

Statistical data processing in Figure 5 by the least square method [6] gives the following results:

$$f_{fr} = 0.008025N_a + 0.05259 \quad \text{with} \quad \rho(f_{fr}, N_a) = 0.9690$$

(3)

where $\rho(f_{fr}, N_a)$ is the correlation coefficient between the coefficient of friction $f_{fr}$ and the intensity of the stream of AE events $N_a$ restored according to (1).

We evaluate the reliability of the determination of $f_{fr}$ by the formula (3). The classical definition of reliability is interpreted as the probability of a measured or diagnosed parameter falling into a certain interval. Moreover, in the case of long tails of the densities of the distribution functions of the values of this interval, sometimes a high reliability of the measurement results of the controlled parameter is sometimes obtained, although in fact these results have zero information content [7].

To overcome this uncertainty, we previously proposed a slightly different approach and introduced the concept of *information reliability* $R$, associated not with probability, but with the amount of information $q$ obtained in the process of evaluating or diagnosing the controlled parameter itself [7]. In this case, we proposed to determine the uncertainty interval through the disinformational effect of the error according to the probabilistic theory of information of C. Shannon [8]. The following simple relations were obtained [7]:

$$R = 1 - \exp(-q) ; \quad R = 1 - \sqrt{1 - \rho^2} ; \quad 0 \leq R \leq 1.$$  

(4)

where $R$ is information reliability; $q$ is the amount of information obtained as a result of the measurement procedure or diagnosis; $\rho$ is the correlation coefficient between the measured and diagnosed parameters.
Figure 5. Graphs of the coefficient of friction (a) and the intensity of the stream of AE events (b).

Substituting in (4) the value of the correlation of the friction coefficient, determined according to (3), with the restored intensity of the AE events, we get that the information reliability $R$ of the estimation of the friction coefficient $f_{fr}$ from the restored intensity of the AE events $\hat{N}_a$ is has a magnitude of about 73.5% (Figure 5).

Figure 6. Determination of the burn-in stage based on the coefficient of friction and the minimum normalized intensity of the restored stream of AE events.
Figure 6 shows our preliminary results on AE estimation of the friction coefficient at the stage of running-in of the material of the movable splined joints of the rotating elements of the world's most lifting Mi-26 transport helicopter. It can be seen (Figure 6) that the points of the end of the running-in time, determined by the coefficient of friction (o) and the normalized intensity of the stream of AE events (●), differ little.

3. Conclusions
By using the AE signals, the obtained results made it possible to quantify the initial concentration and constant multiplication of microdefects in the material of thermal protection tiles of Russian space shuttle Buran. Interesting results were obtained also for AE diagnostics of hydrogen embrittlement of materials and acoustic emission evaluation of the friction coefficient at the stage of running-in of the material of the movable splined joints of the rotating elements of the helicopter. This information can be hardly obtained by any other physical research methods.

Thus, the AE method has good prospects for application in non-destructive testing and diagnostics of the strength of elements of various types of vehicles.

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