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Original article

Acoustic Emission Method of Diagnostics of Structures Made of Composite Materials Based on Invariants

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Abstract

Introduction. Composite materials are the main way to reduce the weight of the aircraft structure and improve its flight performance. Methods of non-destructive testing enable to assess the technical condition of composite materials, as well as to determine stress concentrators in them to make a decision on the further operation of this control object. The paper presents an analysis of the use of composite materials in the aircraft design and ways to improve their flight performance through the application of composites. An acoustic-emission method for assessing crack resistance based on invariants was described. The study aimed at increasing the accuracy and efficiency of assessing the crack resistance of aircraft structures made of composite materials through the use of the acoustic emission method of non-destructive testing.

Materials and Methods. The nomenclature of composite materials used in aircraft was given, and their physical and mechanical properties were compared. The acoustic emission method of non-destructive testing of composite materials based on invariant ratios was used.

Results. A method for assessing the crack resistance of primary structural elements based on the invariants of acoustic emission processes, and a program apparatus complex based on it has been developed.

Discussion and Conclusions. The results obtained can be used to determine the strength characteristics of composite materials by the acoustic emission method of non-destructive testing to assess the technical condition of primary structural elements in mechanical engineering, shipbuilding, and aircraft construction. The paper is recommended to researchers involved in the development of aircraft.

Keywords: composite materials, aircraft, non-destructive testing, acoustic emission control.

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Introduction. Improving aircraft performance characteristics (APC) and reducing the weight of aircraft structures while maintaining their sufficient strength and stiffness is a fundamental task in the aircraft industry [1, 2]. The introduction of composite materials (CM) partially solves this problem.

The developers of flying vehicles (FV) are constantly introducing new materials into aviation technology to increase the APC and reduce the weight of the structure. CM provide reducing the weight of the wing, fuselage and tail. High mechanical-and-physical properties of CM increase the stiffness and strength of the structure.

The major advantages of CM include high values of specific strength, stiffness (modulus of elasticity 130–140 GPa), wear resistance and fatigue strength[1,2] [3, 4]. The disadvantages of CM include hygroscopicity, significant cost, anisotropy of properties, low impact strength, low operational manufacturability.

The study aimed at increasing the accuracy and efficiency of assessing the crack resistance of composite structures through the use of acoustic emission (AE) control.

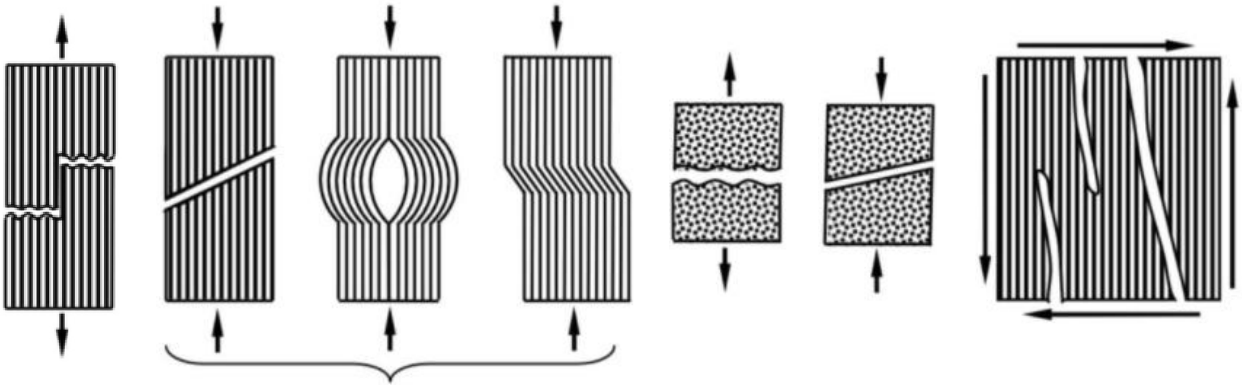
Materials and Methods. A wide range of CM is used in the aircraft industry [1, 4] (Fig. 1), due to which it is possible to lighten the weight of structures. This is achieved by replacing elements made of traditional materials (titanium and aluminum alloys, steel) with CM.

Aviation industry enterprises face two crucial tasks:

– to evaluate the processes of accumulation of damage and destruction of structures from CM in the entire range of alternating loads;

– to evaluate the quality of serial products from CM through strength testing.

Basically, the following CM destruction schemes are distinguished (Fig. 1):



a) *b*) *c*) *d*) *e*)

Fig. 1. Schemes of destruction of composite materials: *a* — when stretched along the fibers; *b* — when compressed along the fibers; *c* — when stretched across the fibers; *d* — caused by shear stresses when compressed across the fibers; *e* — delamination (the authors' figure)

Currently, the acoustic emission (AE) method of NDT is special among the methods of diagnosing high-duty structures.

The AE method is based on the registration of acoustic waves emitted under the destruction of CM. The major advantages of this method include [5–11]:

– complex nature of the CM study (fracture mechanics and acoustic diagnostics);

– registration of developing CM defects;

– high sensitivity to growing CM defects (sensitivity of AE equipment of the order of 1×10^{-6} mm^2 for a crack of CM with a length of 1 μm);

– using multiple converters;

– remote monitoring of objects at a considerable distance from the AE equipment.

AE in CM is a nonstationary random elastic wave emission process. Based on this, methods of static radio engineering can be used to treat and analyze such processes. Based on the Poisson distribution, a well-known equality between the mathematical expectation and the variance of the number of events in a random process is fulfilled:

$$m[x] = D[x] = \lambda, \qquad (1)$$

where λ — intensity of the number of pulses at a given sampling interval.

This relation makes it possible to construct parametric invariants that are valid only for the Poisson process, and on this basis, to estimate the deviation of the analyzed process from the Poisson one [5, 6, 12, 13]:

$$I_1 = (m[x^3] - 3 \cdot m[x^2] \cdot m[x] + (m[x])^3) - m[x] = 0. \qquad (2)$$

[1] Pravila organizatsii i provedeniya akustiko-emissionnogo kontrolya sosudov, apparatov, kotlov i tekhnologicheskikh truboprovodov. PB 03–593–03 RF Gostechnadzor. Moscow: PIO OBT; 2003. 102 p. URL: https://files.stroyinf.ru/Data2/1/4294816/4294816759.htm (accessed: 28.09.2022). (In Russ.)

[2] Ivanov VI, Vlasov IE. Metod akusticheskoi emissii. In: Nerazrushayushchii kontrol'. Spravochnik v 8 t. T. 7. Kn.1. Klyuev VV (ed.) Moscow: Mashinostroenie; 2006. 340 p. (In Russ.)

Expression (15) can be used as an invariant of the number of AE pulses to determine the degree of deviation of the AE pulse flow from the Poisson one when conducting AE tests of CM.

Based on (15), we obtain several more expressions to determine the degree of deviation of the AE pulse flow from the Poisson one:

$$I_2 = \frac{m[x]}{m[\dot{x}^3]} = 1; \quad (3)$$

$$I_3 = \frac{m[x]\left(1-2\cdot\left(m[x]^2\right)+3\cdot m[x^2]\right)}{m[x^3]} = 1. \quad (4)$$

When a macrodefect is formed, the characteristics of AE pulse flows become dependent, which destroys the Poisson flow hypothesis and causes a violation of equality (2–4).

This approach is implemented in the program apparatus complex (PAC) (Fig. 2), which provides identifying crack-like defects in various CM [12, 13].

PAC consists of the following components:

– broadband piezo sensors GT300, operating frequency range —100–800 kHz, resonant frequency 283 kHz;

– amplifier GT200A, gain factor — 1–200, limits of the permissible additional relative error of the charge conversion coefficient in the operating temperature range are from –40 ° to + 85 °C with an error of ± 1 %;

– ADC E20-10 is a high-speed ADC module with USB interface for connecting to a PC, which has four ADC channels 14 bit/10 MHz with multiplexing function, 16 channels of digital input and output compatible with TTL logic, as well as two channels of DAC 12 bit / ± 5 V;

– PC, HF cables.

Accuracy and reliability of the AE registration and processing is provided by the frequency parameters of piezotransducers and ADC, which are consistent with Kotelnikov theorem. It states that a continuous signal with a limited spectrum can be accurately reconstructed from its discrete samples if they were taken with a sampling frequency exceeding the maximum signal frequency by at least two times.

PAC uses software amplitude threshold filtering, as well as a method for smoothing the resonant amplitude of pulse attenuation based on a digital peak detector, which provides obtaining exponential smoothing of the shape of AE pulses to increase the accuracy of their registration.

A technique for evaluating multiparametric information based on combining (“convolution”) informative parameters of AE by methods of the theory of operations research has been developed to perform a complex real-time analysis of a set of informative parameters of AE signals.

The developed software implementation of the technique has the following basic functional modes: setup; function check; input of restrictions and initial data; monitoring changes in loads, deformations and waveforms of AE pulses; a set of informative AE parameters and their “convolution” through registration channels; determining the location of defects; assessing the danger of defects and the possibility of further operation of the structure, storing the results.

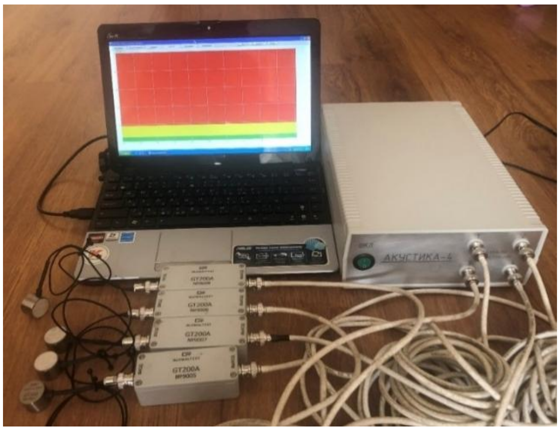
Since AE is a passive method of non-destructive testing, one piezo sensor can register signals from a separate power element of the FV (Fig. 2 *b*).

The elastic wave attenuation, depending on the material, profile and thickness of the tested samples, determines the number of piezoelectric converters used and the distance between them. The attenuation of signals is determined experimentally using an AE signal simulator before testing samples and structural elements.

For fault isolation, the triangulation method[3,4] was taken as a basis, which provides determining the location of defects in the primary structural elements in real time with an accuracy of 0.1 m.

[3] PB 03–593–03. Pravila organizatsii i provedeniya akustiko-emissionnogo kontrolya sosudov, apparatov, kotlov i tekhnologicheskikh truboprovodov. RF Gostechnadzor. 2003. 102 p. (In Russ.)

[4] Nerazrushayushchii kontrol'. Spravochnik v 8 t. Klyuev VV (ed.) In Kn.1.: Ivanov VI, Vlasov IE. Metod akusticheskoi emissii. Kn. 2: Balitskiy FYa, Barkov AV, Barkova NA, et al. Vibrodiagnostika. 2-e izd., ispr. Moscow: Mashinostroenie; 2006. 829 p. (In Russ.)

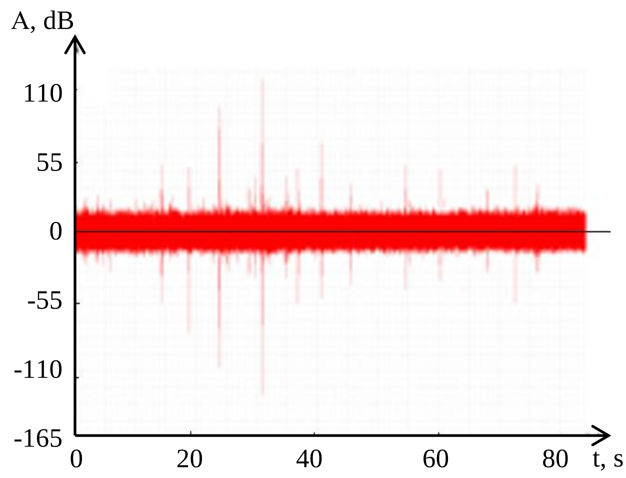


a)

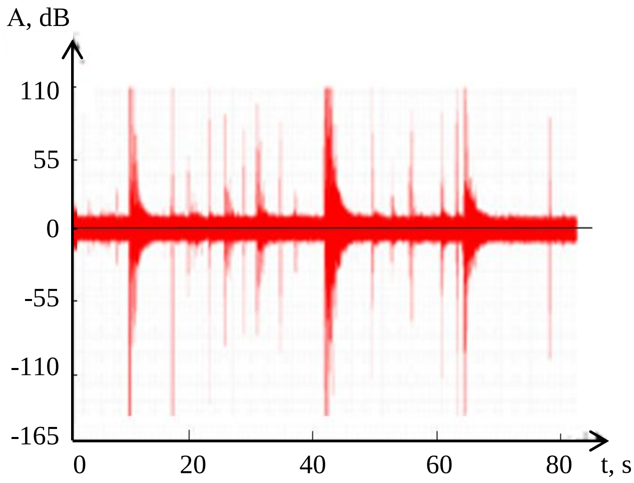
b)

Fig. 2. Program apparatus complex of acoustic emission diagnostics: *a* — complete complex; *b* — placement of the complex sensor under testing of the aircraft aileron on the stand (the authors' photo)

Research Results. To assess the reliability of the proposed invariant method and the sensitivity of the PAC to the assessment of developing defects, strength tests of a series of KM KMU-1B samples were performed before destruction. The load was carried out by the RM-1 breaking machine. Before tensile tests, a piezoelectric sensor was installed on the surface of the sample through a layer of contact lubricant (Tsiatim) to improve acoustic contact. During the tests, acoustic pulses that occur in the structure of the OC when creating a load were recorded. Elastic AE waves were recorded by a piezo sensor, then the signal was amplified by a preamplifier, an analog-to-digital converter transformed the signal into an analog-to-digital form for subsequent processing on a PC. The results are shown in Figure 3:



a)



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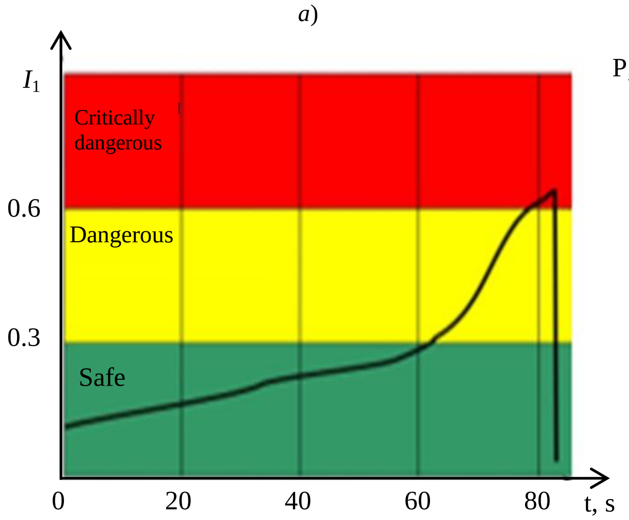
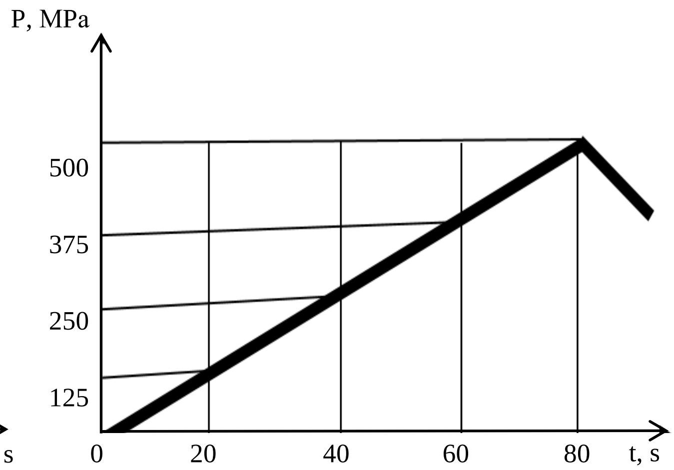
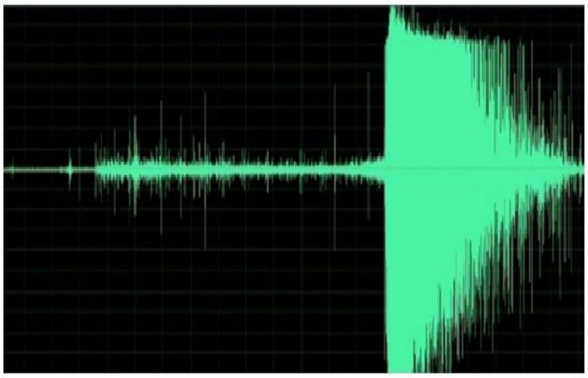


c)



d)



e)

Fig. 3. Experimental results before destruction of the samples: *a* — oscillogram of AE pulses during destruction of the composite material matrix; *b* — oscillogram of AE pulses under destruction of the composite material fibers; *c* — curve of invariant I_1; *d* — loading curve of the glider primary element from CM; *e* — oscillogram of the AE signal from the beginning of the load to the destruction of the sample (the authors' figure)

Figures 3 *a* and 3 *b* show the waveforms of AE pulses during the destruction of the matrix and fibers of the composite material, in which the maximum values of the AE signal amplitude correspond to the destruction of OC. At an amplitude of 55 dB, the CM matrix is destroyed, at 75 dB, the CM fibers are destroyed.

Figure 3 *c* shows the dependence of the invariant on time I_1 (load). The green zone is characterized by the absence of a defect in the primary element of the airframe. The yellow zone is characterized by an unfavorable loading environment of OC, the formation of developing defects (cracks, delamination). The red zone corresponds to the destruction of KMU-1V.

From the 60th second of loading at a load of 375 MPa, the formation of the main crack occurs (Fig. 3 *d*), which causes the exit of the invariant from the green (safe) zone. These conditions correspond to 75 % of the destructive load (350 MPa) of the samples. The reliability of the use of invariants is validated by a sharp increase in the amplitude and intensity of signals (Fig. 3 *e*), the results of optical control during tests.

At a load of P = 500 MPa, the destruction of CM occurs at a time equal to T = 80 s, which causes a decrease in the load and the amplitude of acoustic vibrations in the material of OC.

Discussion and Conclusions. This experiment reflects the acoustic emission control of samples (primary structural elements) from KMU-1V.

The developed PAC, based on the proposed invariant method, makes it possible to process multichannel and multiparametric information about changes in informative AE parameters on-the-fly (in real time), determine the location of defects in CM, assess the degree of danger of defects and the possibility of further operation of structures [12, 13].

In the future, it is proposed to introduce such automatic control systems to diagnose the design of aircraft in flight and during ground maintenance.

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A. V. Popov: development of the invariant method; scientific management of research. V. Yu. Voloshina: conducting and analyzing research results; text layout. K. A. Zhuravsky: development and description of the hardware and software complex. M. A. Labina: analysis of composite materials and flight characteristics of aircraft.

Conflict of interest statement

The authors do not have any conflict of interest.

All authors have read and approved the final manuscript.