Computerized system of acoustic-emission control of metal structures

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Abstract. Research on the problems of creating effective control and diagnostic systems allows us to single out the following areas: the development of the theory and methods for diagnosing and predicting the strength and reliability of structures, theoretical and experimental studies of fracture processes, and the corresponding changes in characteristics and parameters, i.e., carriers of information about the processes occurring in the material during destruction; creation of information-measuring systems designed to register and analyze the information necessary to resolve the issue of the state of the structure; development of software for measuring equipment, including not only the main programs for generating and processing incoming information but auxiliary subroutines that provide information compression, increase the reliability of measurement results, defect recognition, decision making. The article is devoted to the methods of acoustic-emission control of metal structures and developing a computerized system for its implementation. The basics of organizing a software-algorithmic system for locating and processing acoustic emission signals are considered, including methods for discretizing models of sensors and acoustic emission signals, which make it possible to obtain computational schemes such as a digital filter that provide effective algorithmic implementation; description of fragments of an experimental software-algorithmic system for processing acoustic emission signals, illustrating the principle of constructing software tools in an arbitrarily chosen computing area, the structure of the software organization of computational processes for locating an acoustic emission signal, which ensures the construction of the corresponding subsystem of a computer complex for acoustic-emission control, both in single-antenna and in a multi-antenna version.

1 Introduction

One of the characteristic trends in the development of modern technology is the increase in the scale and responsibility of structures and structures, the accumulation of large energy reserves in them. These are long-distance gas pipelines, power plants, large bridges, hydraulic structures, large-scale mobile objects associated with the transportation of many

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people, etc. Deviations in the operating modes or accidents of such structures can lead to serious consequences, therefore, it is not enough to predict the reliability of structures based on the calculation conditions, their strength, and testing. Most structures have been in operation for many decades, and time can make significant corrections to theoretical calculations. An attempt to take them into account when designing due to ignorance of the actual operating conditions of the structure, as a rule, leads to an increase in safety factors. At the same time, the weight of structures increases significantly, leading to excess metal consumption. From the foregoing, it becomes clear that the reliability of products must be ensured and strictly controlled both during manufacture and operation. For this purpose, it is necessary to create effective monitoring and diagnostic systems that can assess a critical situation in time and take the necessary measures to prevent an accident [1].

An analysis of research and development carried out on the problem under consideration makes it possible to single out the following main scientific areas: development of the theory and methods for diagnosing and predicting the strength and reliability of structures, theoretical and experimental studies of destruction processes and the corresponding changes in characteristics and parameters, i.e., carriers of information about the processes occurring in the material during destruction; creation of information-measuring systems intended for registration and analysis of information necessary to resolve the issue of the state of the structure; development of software for measuring equipment, including not only the main programs for generating and processing input information but auxiliary subroutines that provide information compression, increase the reliability of measurement results, defect recognition, decision making, etc. [2].

One of the most promising methods of non-destructive testing is the method of acoustic emission (AE), or otherwise the method of AE-control. It is based on capturing sound signals emitted during the plastic deformation of solid media and the development of defects. The AE method has several advantages, due to expanding the possibilities of non-destructive testing [3-6].

It should be noted that the level of research and development results achieved so far in the field of creating AE control systems does not yet allow for the fully implement the latest achievements of science and technology in specific systems and algorithms to close the chain from the input information to the acceptance algorithms, decisions about the state of objects. At present, the mode of vibrations and the frequency spectrum of AE signals, as the characteristics of their propagation in materials, have not been sufficiently studied, and systematic studies on the restoration of a highly distorted AE signal have not been carried out. This complicates the solution to the problem and requires further research. The available models of AE signals and their converters are, in many cases, simplified and do not fully reflect the real picture. Often, experiments are not reproducible enough. It should be taken into account that to solve the problem of the propagation of elastic waves in a specific structure, it is necessary to build a complex mathematical model [7-13].

It should also be noted that solving the problem of restoring the original AE signal shape allows us to reduce the further problem of fracture prediction to the problem of mechanics with its powerful physical and mathematical apparatus, apply existing computational mathematics tools and ensure the creation of the required control and prediction algorithms [14-16].

The study of acoustic signals emitted by areas of plastic deformation or zones of cracking of solids under mechanical loading and the use of AE signals for monitoring the state and predicting the strength of mechanical engineering objects form the conceptual basis of the AE method [17-19].

2 Methods

Control systems for metal structures based on AE signal processing, depending on their area of application, functional and communication capabilities, and accuracy characteristics, can differ significantly in complexity and equipment composition. However, despite the differences, all such systems must satisfy some general requirements, namely:

1) to process incoming information in real-time;
2) ensure long-term trouble-free operation in continuous operation;
3) have the means for documentary registration, large amounts of information in a form convenient for storage and subsequent machine processing;
4) to carry out operational analysis (express analysis) and display measurement results;
5) maintain performance under various external influences (industrial noise, vibration);
6) operate at a significant distance of the equipment from the test object.

In addition to these requirements, when creating acoustic emission control systems, the principle of modularity should be observed, and the systems themselves should have a hierarchical structure. The hierarchical system of acoustic emission control, the structure of which is shown in fig. 1, contains sensors S that can be combined into groups (antennas), a device for preprocessing the results of measurements of location parameters (DPRM-V), a device for preprocessing the results of measurements of diagnostic parameters (DPRM-D), a specialized coordinate calculator (SCC) of AE sources, a specialized calculator of diagnostic parameters (SCDP), recorder (R), interface device (ID) with a computer for intermediate processing of diagnostic information (COMPUTER - I), computer for statistical processing and decision making (COMPUTER-D).

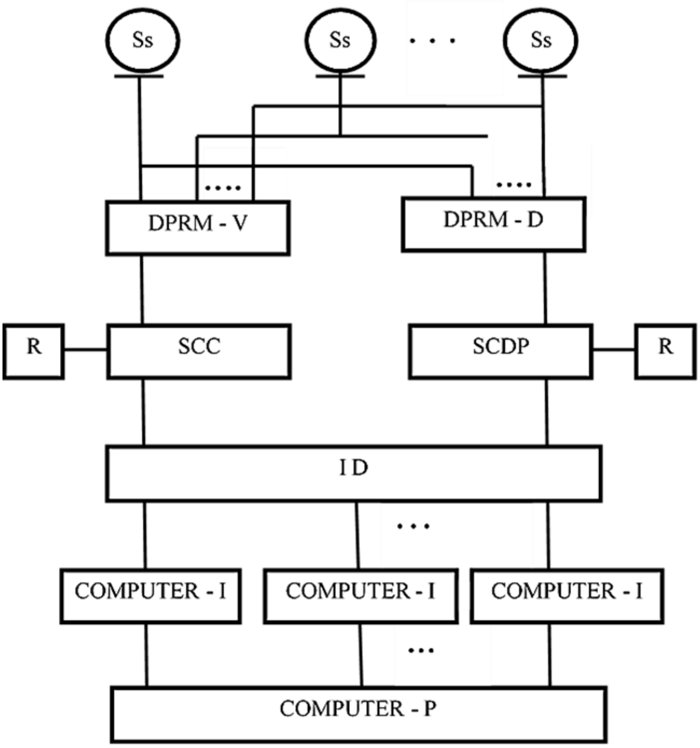

Fig. 1. Hierarchical system of acoustic emission control.

AE sensors are electroacoustic transducers and are one of the main elements of acoustic emission diagnostic systems. DPRM-V registers and converts into a code the time parameters of the AE signal, for example, the time of the beginning of the mode, the time of the end of the mode, and the arrival time difference (RTD) modes for different sensors. A mode is a part of the AE electrical signal envelope at the output of the receiving transducer, located between two adjacent minimum values and having one maximum in this interval.[20] DPRM-D pre-amplifies, limits, and converts the AE electrical signal into digital form. In DPRM-V and DPRM-D, buffering (intermediate storage) of preprocessing results is also carried out.

The SCC of AE sources and SCDP carry out the calculation of the coordinates of sources and express analysis of AE signals in real-time, as well as the operational registration and display of processing results on the recorders R. ID is designed to ensure the coordinated operation of SCC and SCDP in combination with upper-level computers and provides telecommunication access to them. Low-power computers or blocks are used as intermediate processing computers, while more powerful computers are required for static processing and decision-making.

Localization of sources allows separating information from different defects and performing spatial filtering, which means that the display of AE signals associated with a developing defect is concentrated at its location. In contrast, signals caused by extraneous, non-local phenomena, for example, noise, as a rule, either does not have a specific location or is concentrated in pre-known places, due to the specific layout of the receivers and the features of the controlled design.

In this regard, constructing SCC AE sources operating in real-time is a priority task in creating systems for acoustic emission control and diagnostics.

DPRM is designed to detect an AE signal and extract information features from it by analog-digital processing for subsequent mathematical processing using a computer.

DPRM-V location signs, a variant of the structure of which is shown in fig. 2, contain $n \geq 3$ measurement channels, where n is the number of sensors Ss used in the AE control system, each of which consists of an amplifier A, a comparator C, a detector (Dr), a selector S, registers Rg. The DPRM-V also includes the control unit CU and the interface unit IU with the SCC. The connection of the DPRM with the sensors Ss is carried out via cables. Amplifier A is designed to amplify the signal coming from sensor Ss. Comparator C is designed to highlight the part of the AE signal that exceeds the discrimination level u_Δ ; the choice u_Δ depends on the noise level during the control.

The detector Dr performs the formation of a pulse, the beginning of which coincides with the moment of registration of the next mode of the AE signal by the sensor, which has a duration equal to the duration of the mode. Selector S generates short pulses at times corresponding to the beginning and end of the mode, the beginning, and end of the mode registered in the selected channel, etc. The registers Rg are used for intermediate storage of location features for their subsequent transmission through the IU interface unit for processing the SCC. The CU control unit synchronizes pre-treatment processes in a given mode, which is set from the control panel via external communication lines.

DPRM-V, whose structure is shown in fig. 2, works as follows. After the "Reset" signal arrives at the second input of the CU control unit, zero signals are set at its outputs, and all units of the device are set to their initial state. After the "Start" signal arrives at the third input of the control unit, current time codes begin to be continuously issued from its first output, which are fed to the second inputs of the Rg registers of each measurement channel $i(i = 1,...n)$. The AE signal recorded and converted by the sensor Ss, after amplification in the amplifier A, is fed to the input of the comparator C. In comparator C, the part of the AE signal that exceeds the noise is isolated by limiting the lower limit to the voltage level u_Δ, the value of which depends on the operating conditions. At the same time, in each measurement channel $i(i = 1,...n)$, the time of appearance of the next mode of the AE signal will be different, depending on the location of the sensor Ss relative to the source of AE signals. At the output of the comparator C, "packages" of pulses of the level of a logical unit of digital elements are formed, the pulse repetition period in the "package" is equal to the oscillation period of the high-frequency filling of the resonant sensor Ss, and the duration of the "package" of pulses is equal to the duration of the mode at the level limited by the comparator C. The signal from the output comparator C is fed to the input of the detector Dr, in which the "packages" of pulses are converted into a continuous signal of the level of a logical unit, having a duration equal to the duration of the mode at the limiting level. Through the edge of the signal generated by the Dr detector, a short pulse of the beginning of the mode is generated in selector S, and the signal decay generates a short pulse of the end of the mode.

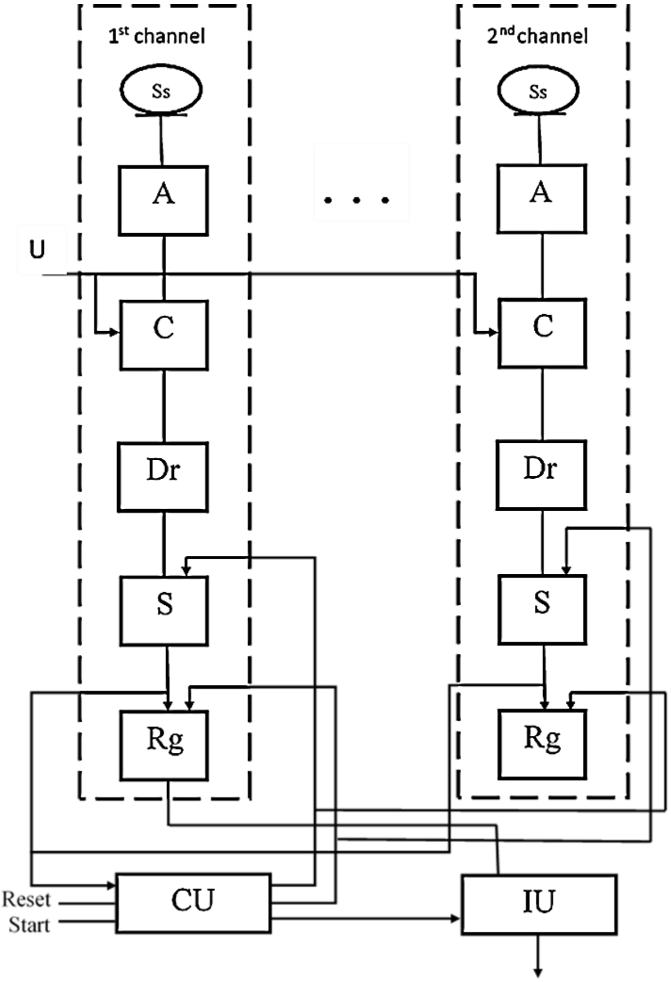

Fig. 2. Device for preliminary processing of results of measurement of location parameters (DPRM-V).

Depending on the operating mode set from the control panel through the control unit of the control unit, selector S can generate pulses of the beginning and end of the mode registered in any other selected measurement channel, an impulse corresponding to the maximum value of the mode duration (used when analyzing the reliability of time intervals). According to the pulses coming from the output of the selector S to the first inputs of the register Rg and the control unit CU, control signals are generated for writing to the register Rg, in which, depending on the mode of operation, either the start/end times of the mode, or the RTD for the selected sensors, or the maximum RTD in the corresponding channel. According to the signal coming from the third output of the control unit CU to the control input of the IU interface unit, the information recorded in the registers Rg of the measuring channels is transmitted for further processing through the IU interface unit.

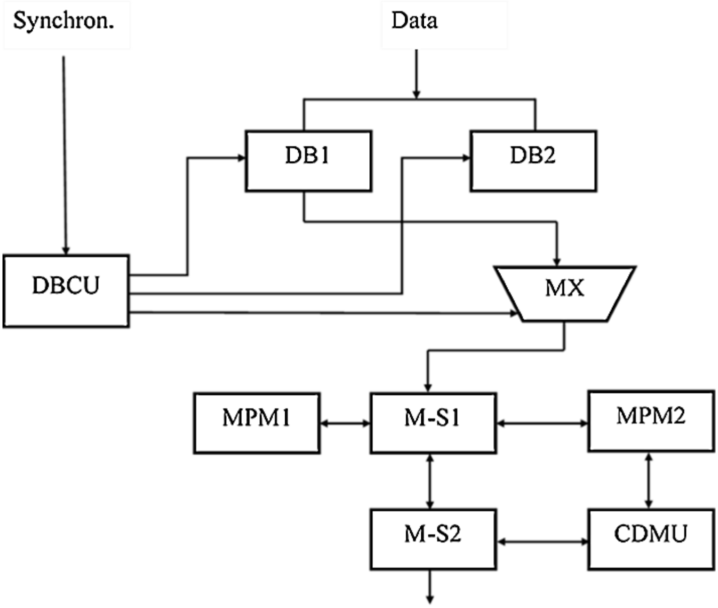

Fig. 3. The structure of the SCC, which implements the single-antenna processing algorithm.

Calculation of the coordinates of AE sources is carried out by the SCC. The structure of the SCC, which implements the single-antenna processing algorithm, is shown in fig. 3. The SCC contains a control unit CU for data buffers DB1 and DB2, microprocessor modules MPM1, MPM2, an MX switch, multiplexers-selectors M-S1 and M-S2, a common data memory unit CDMU. Two data buffers, DB1, and DB2 are introduced to increase the throughput of the SCC and alternately operate in write-read modes. While the data from one buffer is being processed, the other one is being filled with new data.

SCC works as follows. According to the synchronization signal arriving at the first input of the data buffer control unit DBCU, from the first output of the DBCU control unit, signals for setting the operating mode are issued to the control inputs of the data buffers DB1 and DB2. Moreover, if the "Write" mode is set for the DB1 buffer, then the "Read" mode is set for the DB2 buffer and vice versa. According to the readiness signals of the microprocessor modules MPM1 and MPM2, arriving at the second and third inputs of the control unit DBCU, at the second output of the control unit DBCU, a control signal for the MX switch is generated, which connects the corresponding data buffer (DB1 or DB2) to the input bus of the M-S1 multiplexer-selector, which can carry out data transmission on four bidirectional buses with multiplexing and selection under the control of microprocessor units.

So, for example, according to the readiness signal of microprocessors, data is transferred from the corresponding buffer to the common memory of the CDMU, and according to the last processing command, information is issued from the data memory of the CDMU through M-S2 for further processing or display. In specialized devices, processing algorithms, as a rule, do not change. Therefore, programs can be written to ROM or PROM. To provide some functional flexibility of a specialized SCC, it is possible to ensure the program memory's interchangeability through appropriate structural elements for fixing ROM chips (PROM).

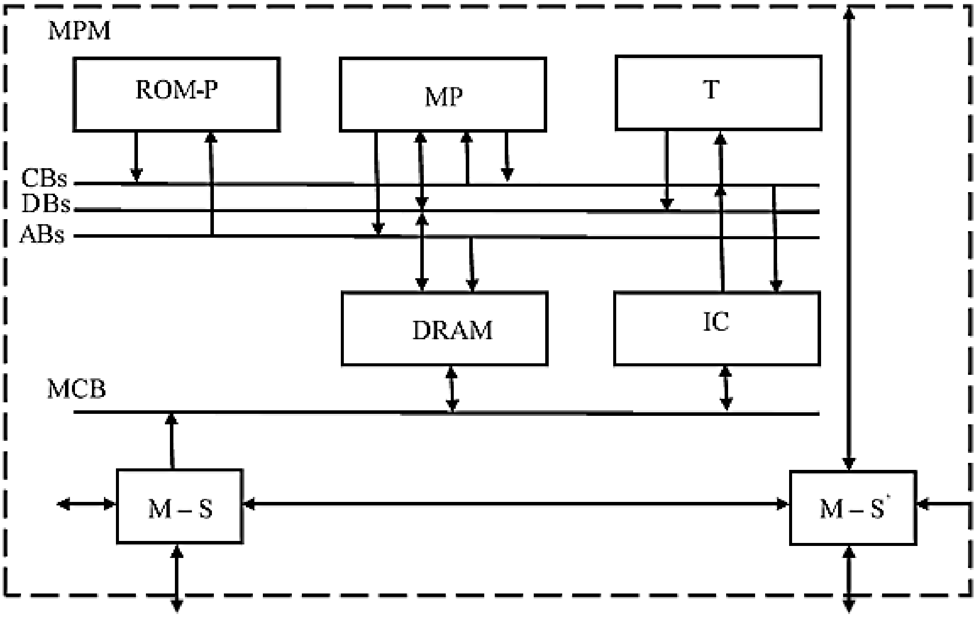

Fig. 4. Structural diagram of the microprocessor module (MPM).

The use of a common data memory of the CDMU requires taking into account possible conflict situations that arise during the operation of microprocessor systems, such as, for example, simultaneous access to memory, invalid modification of the contents of memory, etc. avoid conflicts. The expansion and complication of tasks solved on a specialized multiprocessor system with a shared data memory put forward the requirements for increasing its flexibility. In this case, the problem of unresolvable conflicts may arise. To avoid this, it is necessary to introduce a priority system for servicing requests, blocking memory in case of unauthorized access, etc., which leads to an increase in hardware and can significantly reduce the system's efficiency as a whole due to waiting for permission to access memory. These shortcomings are devoid of a multiprocessor system in which each microprocessor module MPM has its own (local) data memory. Such a module can be considered a stand-alone processor equipped with means for high-speed data exchange and operation synchronization with other similar processors. The block diagram of such a block is shown in fig. 3.

The microprocessor module (MPM), the structure of which is shown in fig. 4, contains ROM programs ROM-P, microprocessor arithmetic logic device MP, programmable timer T, dual-port RAM DRAM, programmable interrupt controller IC, multiplexer-selector M-S.

Communication between MPM nodes is carried out through separate control buses (CBs), data (DBs), and addresses (ABs). Interaction with other MPMs is carried out through the microprocessor communication bus (MCB) with the help of M-S. To expand the communication capabilities of the MPM, an additional multiplexer-selector MS can be introduced into it. Structures consisting of such MPMs have several advantages. The main one is the uniformity of its constituent modules, which ensures high reliability, maintainability, and ease of maintenance. Another important advantage is the ability to build multidimensional parallel structures for solving field theory problems, signal recovery, etc. In addition, such structures do not have the main drawback of multiprocessor systems with a common bus - the discrepancy between the exchange time and the performance of processor modules. One problem that arises when creating such systems is the problem of their effective programming and synchronization of computational processes. However, given the development of such areas as automation of programming of multiprocessor systems, scheduling theory, and the theory of parallel computing, we can assume that this problem will be solved.

3 Results and discussion

Calculation of the power of information flows according to the AE methodology. The processing of acoustic emission signals to determine a defect's location before its identification requires a large amount of computational work, which is associated with the processing algorithms' complexity and the amount of information being processed.

Developing an appropriate control system (CS) requires a preliminary assessment of the power of the processed information flows that arise when using the AE technique. The main purpose of such assessments is to substantiate the structure and composition of the CS.

In the process of testing a product according to the AE method, the main characteristics that determine the amount of information processed are the following:

- f_{fl} is the average frequency of outbreaks of AE acts;
- Ψ_{fl} is average flash duration;
- N is the number of modes in one burst;
- Γ_m is the duration of the mode;
- f_γ is the upper frequency of the AE signal (in the case of a broadband sensor) or the resonant frequency of the AE sensor (for resonant type sensors);
- n is the number of ADC samples for the period determined by the frequency f_γ of the AE signals;
- T_{test} is product testing time;
- K is the number of channels of the AE signal processing system (the number of "fours" of multi-element acoustic antennas).

The presence of the indicated characteristics of AE signals that arise during testing makes it possible, in principle, to organize the solution of location problems, as well as the identification of defects through appropriate processing.

The presence of two main tasks of processing AE signals - identification location - determines two groups of processing algorithms. In contrast, algorithms for solving the location problem are characterized by a small amount of processed information and the requirement for fast processing due to the need to obtain location results in real-time.

When solving the location problem, we obtain the characteristic of the information flow in the form of an upper estimate for the total number of data processing operations of one mode. Consider the main subtasks of the location problem.

I. Determining the angle of direction to the AE signal source (wavefront - flat)

$$\varphi = arctg\frac{t'_{4.1} - t'_{2.1}}{t'_{3.1} - t'_{1.1}} + \Delta\varphi$$

where

$$\Delta\varphi = \begin{cases} 0^0, when\ m = 1 \\ 90^0, when\ m = 2 \\ 180^0, when\ m = 3 \\ 270^0, when\ m = 4 \end{cases}$$

m is the serial number of the sensor in the antenna that received the signal first.

$$\left.\begin{matrix} t'_{j,1} = t_{j-m+1, when\ j \geq m} \\ t'_{j,1} = t_{5-m+1, when\ j < m} \end{matrix}\right\} or \begin{cases} circular\ shift\ of \\ T_1(4)\ array \\ to\ the\ left\ by\ (m-1) element \end{cases}$$

$$(m-1)max = 3$$

$$\min = 0.$$

t $_{j,i}$ is registration time j - with type i wave sensor

$$\begin{pmatrix} i = 1 - \ longitudinal\ wave \\ i = 2 - shear\ wave \end{pmatrix}$$

II. Determining the distance to the AE source by the difference in the type of waves (the wavefront is flat).

$$v_i = \frac{B}{\sqrt{(t'_{4,i} - t'_{2,i})^2 + (t'_{2,i} - t'_{1,i})^2}}; B = b\sqrt{2},$$

B is the base of a multi-element acoustic antenna.

III. Determining the distance to the AE source by the triangulation method (the wavefront is flat).

$$T_1 = \frac{b}{(t_3 - t_4) - (t_2 - t_1)} \times$$

$$\times \sqrt{\frac{[(t_3 - t_1)((t_2 - t_1)(t_2 - t_3) - (t_2 - t_1)(t_3 - t_4))]^2 + [(t_4 - t_2)((t_2 - t_1)(t_3 - t_4) - (t_4 - t_1)(t_2 - t_3) - (t_3 - t_1)]^2}{(t_3 - t_4) - (t_2 - t_1)}}$$

here $t_j = t_{j,1}$.

As can be seen from the above descriptions of the stages, the solution to the location problem, the amount of initial data is:

- with a combination of A and B - N - the number of the sensor that received the signal first; B is antenna base; $T_1(4)$ is array of times of longitudinal wave registration by antenna sensors;
- with a combination of A and B (as well as A, B, and C - $T_2(4)$ - an array of shear wave registration times by antenna sensors.

Let us estimate the number of calculations in solving the location problem for the case when all three stages (combinations I, II, III) are performed.

1. Determination of the angle $\varphi(I)$:

$$\mathrm{t}_{\varphi} = (\mathrm{m}-1)\mathrm{t}_{.\text{ñäâ}} + 3\mathrm{t}_{+} + \mathrm{t}_{\mathrm{g}} + \mathrm{t}_{\mathrm{arctg}}$$

Here and below, the following designations are accepted: t_{+} is summation-subtraction time; $t_{\text{сдв}}$ is shift time; $t_{\text{д}}$ is the division time; t_{y} is multiplication time; $t_{\sqrt{}}$ is time of taking the square root; t_{KB} is squaring time; t_{arctg} is time to execute the *arctg* operation.

2. Distance to the AE source according to the wave path difference (II):

$$t_{\text{ä}} = 2\left(t_{+} + t_{\text{êâ}} + t_{+} + t_{\text{êâ}} + t_{+} + t_{\sqrt{}} + t_{\text{ä}}\right) + t_{\text{ó}} + t_{+} + t_{\text{ṕ}} + 4t_{+} + 3t_{+} + 2t_{\text{ñäâ}} + t_{\text{ó}}$$
$$= 6(t_{+}t_{\text{ó}}) + 2t_{\sqrt{}} + 10t_{+} + 3t_{\text{ó}} = 16t_{+} + 9t_{\text{ó}} + 2t_{\sqrt{}}.$$

2. Distance to the AE source by the triangulation method (III):

$$t_{\text{ä}1} = 6t_{+} + t_{+} + t_{\text{ó}} + 2t_{\text{êâ}} + t_{+} + 2t_{\text{ó}} + t_{+} + t_{\text{ó}} + t_{\text{êâ}} + t_{+} + 3t_{\text{ä}} + 2t_{+} + t_{\text{ó}} + t_{\text{êâ}} + t_{\text{ó}} + t_{\sqrt{}}$$
$$+ t_{\text{ó}} = 11t_{+} + 14t_{\text{ó}} + t_{\sqrt{}}.$$

The obtained data on the time spent on solving the location problem can be used to obtain estimates of the over-volume of calculations if we reduce the execution times of various operations to some single operation. Usually, the reduction is carried out to the operation of addition. Some assumptions are used, as well as empirical data. In this case, these are the following conditions: $t_{\text{сдв}} = t_{+}$, $t_{\text{кв}} = t_{y}$, $t_{\sqrt{}} = t_{arctg} = 2t_{+}$, $t_{y} = 1{,}25t_{+}$, $t_{\text{д}} = 2{,}5t_{+}$. Under these conditions, we obtain the following equivalent computational volumes expressed in the number of addition operations:

$$R_{y} = 30,$$
$$R_{\text{д}1} = 48,$$
$$R_{\text{д}2} = 67.$$

Thus, the total number of operations reduced to the addition in solving the location problem can be estimated as 150 operations per mode.

The characteristics of the information flow in solving the problem of identifying a defect by AE signals largely depend on the accepted ideology of building a recognition system, and their a priori assessment is very difficult. At the same time, given that the purpose of the study is to obtain information for a reasonable choice of the structure and composition of the CS as the main characteristic of the information flow in the decision before identification, it is necessary to accept the amount of initial data, which to a certain extent characterizes the complexity of the task and allows you to obtain rough estimates of the necessary performance (using, for example, a numerical experiment).

The volume of processed information is determined by the following factors (concerning one channel):

a) number of counts per mode : $P_{m} = n\tau_{m}f_{y}$;

b) the average number of AE flashes during the test: $M_{\text{AE}} = T_{test}f_{fl}$;

c) average number of modes during testing: $M_{m} = NM_{\text{ÂÝ}}$;

In this case, the total number of readings during the test (the total number of words of the initial information)

$$W_{c} = M_{m}P_{m};$$

Assuming a two-byte representation of words and taking into account the multi-channel nature of the AE signal processing system, we finally obtain the amount of initial information (in megabytes)

$$W = 2\cdot 10^{-6}K\cdot N\cdot T_{test}\cdot f_{fl}\cdot n\cdot \tau_m\cdot f_{\partial}$$

Following the experimental data on the analysis of acoustic emission signals and the testing technology, for the quantities that determine the amount of information estimated above, we have the following estimated values:

$$f_{fl} = 1e^{-1};\ N = 100;\ \Gamma_m = 20\cdot 10^{-6}\text{c};\ f_e = 3\cdot 10^5 e^{-1};\ n = 20;$$
$$T_{test} = 1{,}5\cdot 10^4\ \text{c};\ k = 1{,}4.$$

Using these data, we obtain the following rough estimate from above of the amount of information processed when solving the problem of identifying the amount of information
$W = 2\cdot 10^{-6} 4\cdot 10^2 1{,}5\cdot 10^4\cdot 1\cdot 20\cdot 20\cdot 10^{-6}\cdot 3\cdot 10^5 = 1440$
(Megabyte)

The obtained estimates of the characteristics of information flow in solving the problems of location and identification of defects by analyzing acoustic emission signals make it possible to constructively formulate certain requirements for computing facilities.

4 Conclusion

Based on the formulated transformations to the functioning and composition of the computerized acoustic emission control system, its structure of a hierarchical type is proposed, the creation of which implies the use of the principle of modularity. The structure provides for constructing a control system in the form of software-algorithmic tools implemented on a serial computer or in software and hardware form using special processors. To determine the resource of the used computer (hardware) part of the monitoring system, a method is proposed for calculating the power of information flows that display computer analysis of AE signals.

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