AUTOMATED INTELLIGENT METHODS FOR ACOUSTIC EMISSION TESTING DATA PROCESSING

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Introduction

Acoustic emission testing is one of the most sensitive nondestructive testing methods. It allows detecting defects at their initiation and preventing development of such defects.

Thanks to high sensitivity, the acoustic emission method is used extensively for nondestructive testing and technical condition monitoring of complex industrial facilities, buildings and structures.

Acoustic emission (AE) testing is a passive NDT method, therefore its main stages are measurement and processing of AE data according to diagnostic model of the testing object. The reliability of detection and the accuracy of determination of AE source location depend on the correct interpretation of AE testing results.

During AE data analysis the following tasks are solved – recording of test object surface oscillations generated by acoustical emission waves, noise filtering and interference elimination, detection and location of potential acoustic emission sources, evaluation of their hazard level.

Because of AE signals nonstationarity and non-availability of accurate diagnostic models, each of above mentioned tasks represents a serious scientific problem that requires a fundamental mathematical apparatus for solution. Up-to-date acoustic emission testing systems contain complex software, including various analysis utilities for filtering data and signals time-frequency analysis, classification and statistical processing.

As a rule, intelligent software for AE systems is not automatized and is designed only for off-line data analysis. Absence of automation at analysis of the data essentially reduces its importance, as along with extra options for diagnostic information processing, it imposes high requirements for user’s qualification.

Besides, interactive software application is nearly not possible for field on-line data analysis, when reliability of testing results is of special importance.

One of our company’s areas of activities is carrying out of scientific researches focused on practical application – increase of accuracy and reliability of AE testing results, and complex industrial facilities investigation.

Researches resulted in creation of automated algorithms to provide intellectual support of AE testing procedure and data processing at all stages: from data measuring up to off-line processing.

1 Automation Concept

In the course of acoustic emission testing one may distinguish three main stages: preliminary stage, data collection and data analysis.

At preliminary stage calibration measurements are performed to determine acoustic properties of test object and acoustic emission sensors sensitivity. To increase AE testing productivity, preliminary calibration may be performed in automatic mode by means of acoustic emission wave simulators or sensors intrinsic emission instead of routine manual procedure with help of Hsu-Nielsen-Sourse.

The automated calibration measurements allow to define more exactly AE sensors coordinates; estimate location speeds and determine quality of acoustic contacts between sensor and test object surface.

Along with measurement chain calibration in on-line mode acoustic signal reconstruction is possible. That is provided by inverse filtering. With help of deconvolution it is possible to decrease influence of AE sensor impulse response and reconstruct acoustic signal waveform that increases analysis reliability.

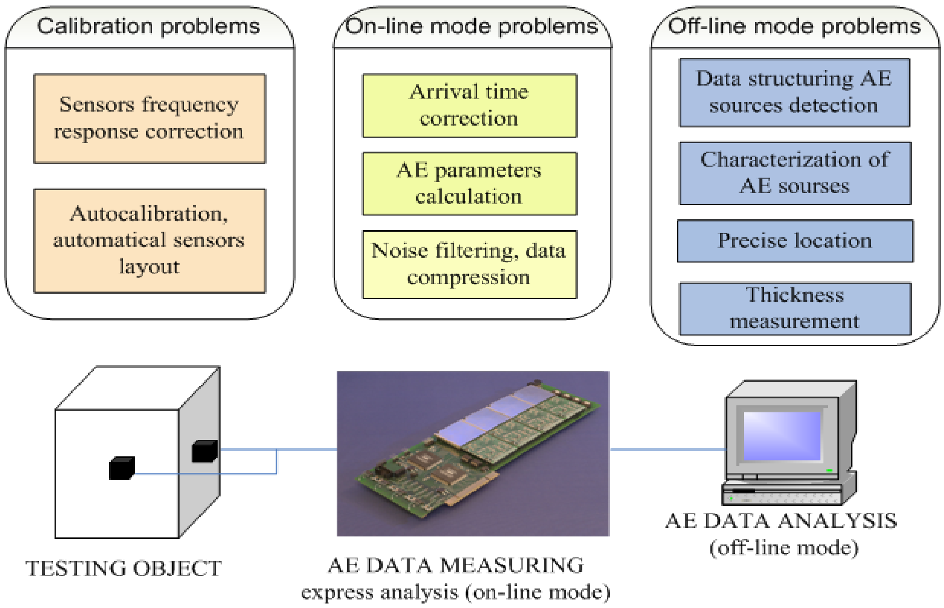

Fig. 1 Flowchart of automated data processing at acoustic emission testing

To improve noise immunity of acoustic emission testing at data measuring stage, various filtration algorithms are applied. The most effective one is using filtration schemes based on signal wavelet decomposition. Wavelet transformation allows estimating AE parameters with regard of multicomponent model of signals, specifying AE impulse arrival time and performing effective compression of AE signals.

In the course of delayed data analysis intellectual processing capabilities are not limited by high frequencies of data recording. In the post-processing mode automatic AE data structuring is possible. Via clustering analysis AE signals and impulses, relating to the same acoustic emission source, are grouped in clusters. Results of clustering are used in the following to clarify dangers level of potential defects.

During AE testing one of the most reliable defined parameters is coordinates of AE sources; to increase accuracy of results, the delayed analysis uses precision location schemes, considering dispersive character of acoustic emission waves propagation in thin-wall structures.

In the course of acoustic emission monitoring intellectual data processing allows to fulfill thickness measuring functions – evaluation of test object wall thinning due to degradation. Measurements of the average wall thickness are based on Lamb wave dispersion and resonances. Thickness determination accuracy in that case does not exceed units of percents.

2. Calibration and Service Measurements

When carrying out the acoustic emission testing, the procedure begins from a preliminary stage, during which sensors are placed on the object surface, test and calibration measurements are conducted, serviceability and sensitivity of the measuring channel are assessed, as well as the propagation velocity and the attenuation coefficient are determined.

The preliminary measurements are a long-term, routine procedure which frequently presents severe engineering difficulties. For example, in case when there is no free access to the test object surface, in case of high-rise buildings and structures testing, or when temperature of the test object surface is very low or very high.

Increase in efficiency and accuracy of the preliminary measurements, and also simplification of the operator's actions at this stage may be achieved at the cost of the calibration measurements automation.

The majority of up-to-date acoustic emission systems allows for carrying out the automated calibration measurements. The approach under study has an advantage of the integrated solution of a problem – all calibration measurements are carried out and all settings are determined within the limits of one automatic algorithm.

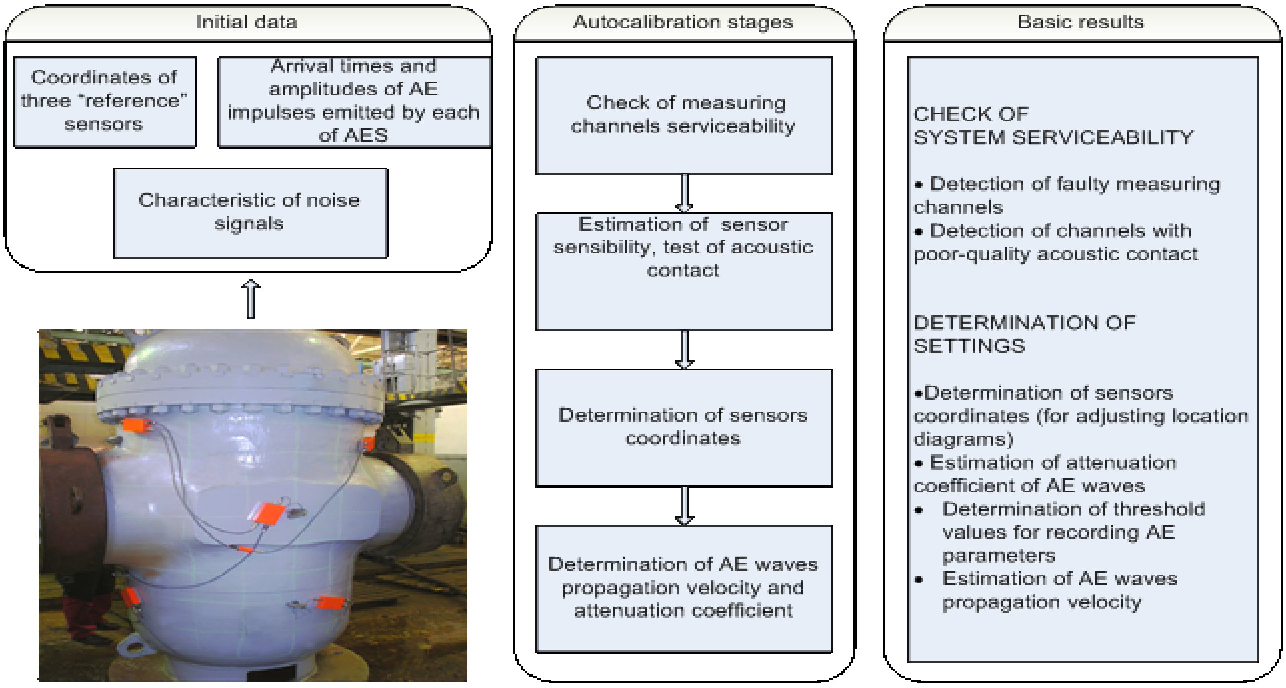

Fig.2 Diagram of Acoustic Emission System Autocalibration

Fig.2 shows the automated diagram of acoustic emission system autocalibration. The autocalibration stage begins immediately upon connection to the system of measuring channels and installation of the sensors on the test object surface. For algorithm successful operation it will suffice to measure manually coordinates of several reference sensors, all other parameters are determined automatically. During autocalibration the sensors are used in a mode of background noise measurements for estimating the level of acoustic noises and in a mode of emission when all sensors are alternately used as simulators of AE waves to be recorded by other sensors.

Based on the evaluations of noises $(n_1 \quad n_2 \quad n_3 \quad . \quad . \quad . \quad . \quad n_m)$ to be recorded for each acoustic channel, amplification factors of the measuring channels are adjusted and thresholds for recording the primary diagnosis information are determined. It is convenient to represent the results of measurements, received in a mode of emission, in matrix form, (1) and (2) – matrixes of amplitudes and differences of arrival times of the recorded AE signals, where A_{ij} is an amplitude of acoustic emission impulse emitted by i-th and recorded by j-th sensor, while Δt_{ij} is a difference of times between AE wave emission by sensor i and its record by sensor j.

$$\begin{pmatrix} A_{11} & A_{21} & A_{31} & . & . & . & . & A_{n1} \\ A_{12} & A_{22} & A_{32} & . & . & . & . & A_{n2} \\ A_{13} & A_{23} & A_{33} & . & . & . & . & A_{n3} \\ . & & & . & & & & . \\ . & & & & . & & & . \\ . & & & & & . & & . \\ . & & & & & & . & . \\ A_{1n} & A_{2n} & A_{3n} & . & . & . & . & A_{nn} \end{pmatrix} \quad (1) \qquad \begin{pmatrix} \Delta t_{11} & \Delta t_{21} & \Delta t_{31} & . & . & . & . & \Delta t_{n1} \\ \Delta t_{12} & \Delta t_{22} & \Delta t_{32} & . & . & . & . & \Delta t_{n2} \\ \Delta t_{13} & \Delta t_{23} & \Delta t_{33} & . & . & . & . & \Delta t_{n3} \\ . & & & . & & & & . \\ . & & & & . & & & . \\ . & & & & & . & & . \\ . & & & & & & . & . \\ \Delta t_{1n} & \Delta t_{2n} & \Delta t_{3n} & . & . & . & . & \Delta t_{nn} \end{pmatrix} \quad (2)$$

In conditions of the prior uncertainty the sensitivity of sensors and the quality of acoustic contact are estimated on the basis of symmetry of matrix **A** (1). As the characteristics of the acoustic path at AE wave propagation from sensor *i* to sensor *j* are identical to the characteristics at back propagation, the equation $A_{ij} = A_{ji}$ guarantees the equal sensitivity of measuring channels and the high degree of acoustic contact of sensors *i* and *j*. In virtue of the estimation of the symmetry of emission and receipt parameters, the estimations of operation quality of the measuring channel Q_i (3) are carried out. The received estimations can be reduced to any, user-friendly, scale by means of the weight parameter Δ.

$$Q_i = \frac{\Delta}{N} \sum_{j=1}^{N} \frac{\left| A_{ij} - A_{ji} \right|}{A_{ij}} \qquad (3)$$

Besides testing the serviceability of acoustic emission systems at the autocalibration stage determined are the settings for algorithms of AE data analysis, which are the sensors coordinates, the attenuation coefficient and the propagation velocity of acoustic emission waves. The propagation velocity of AE waves is approximately estimated on the basis of the difference in times of AE impulses arrival to the “reference” sensors whose coordinates are determined manually. The attenuation coefficient is determined according to the difference of AE impulses amplitudes recorded by the “reference” sensors.

The next stage of acoustic emission system autocalibration is the determination of coordinates of all sensors [1,2]. With the propagation velocity of acoustic emission *c* and the propagation times between each AE pair Δtij known, the distances between the sensors are determined as $\Delta X_{ij} = c\Delta t_{ij}$. To determine the sensors coordinates, the iterative algorithm is proposed for use wherein at the initial stage the AE sensors coordinates are set arbitrary. At the subsequent iterations the coordinates are corrected in such a way (4) that the times of waves propagation between sensors correspond to matrix (2) resulting from the calibration measurements,

$$\mathbf{X}^{k} = \mathbf{X}^{k-1} + \mathbf{F}^{k} \varepsilon \qquad (4),$$

X^k and X^{k-1} are coordinates of AE sensor at the iterations k and k-1. F^k is a correction vector that determines a magnitude to which the values of coordinates at k-th iteration will be corrected, ε – constant that determines the convergence rate of iterative process. Correction magnitudes are defined by formula (5), proportionally to the difference between the true values of distances $\Delta X_{ij} = c\Delta t_{ij}$ and the current values ΔX_{ij}^{k}

$$F_i^k = \sum_{j=1}^{N} \alpha_{ij} \left(\Delta t_{ij} c - \Delta X_{ij}^{k} \right), \qquad (5)$$

where α_{ij} – weighting factors.

3. Data Filtering and Compression

One problem of the acoustic emission testing is a great number of noises affecting the diagnosis results. Electric noises, electromagnetic interference, background acoustic noise, rubbing noises are far from the full list of noises present under measurements. At the high level of noises the operator has to increase the recording threshold of the acoustic emission impulses through reducing the testing sensitivity. False determination of AE parameters can result in wrong location and false determination of the AE source danger level. To improve the noise immunity of the acoustic emission system, the data filtering algorithms are to be used.

The A-Line system (Interunis company) represents various algorithms of AE signals processing, which improve the noise immunity of acoustic emission testing.

- frequency filtering (FIR and IIR filter, filters with an arbitrary transfer function)
- filters for removing an additive white noise
- suppression of impulse distortion

The traditional frequency filtering is applied when the signal and noise lie in the different frequency ranges. Application of low-frequency, high-frequency, band-pass and band-rejection filters allows for allocating the frequency ranges which correspond to the diagnostic signal of acoustic emission.

On the basis of digital filtering the signals integration and differentiation can be carried out, if required. The possibility to define an arbitrary shape of the filter transfer characteristic allows for carrying out a deconvolution operation or inverse filtering, that results in compensation of distortions contributed into the signal by the measuring path.

The impulse noises are widespread: various electric and electromagnetic noises (Fig. 3 a, b) occurring if any grounding-related problem arises or if principles of electromagnetic compatibility are violated. Application of the frequency filtering for removing the impulse noises does not result in an acceptable solution, because the noise-like impulse signals have wide spectrum overlapped with spectrum of acoustic emission signal. The median filtering is applied for suppressing the impulse noises. A one-dimensional median filter is a sliding window including an odd quantity of signal readings. The central reading is replaced with the median of all readings in the window. When selecting the filtering window that exceeds duration of impulse components of noises, the last will be suppressed, while energy of the acoustic emission signal will decrease insignificantly.

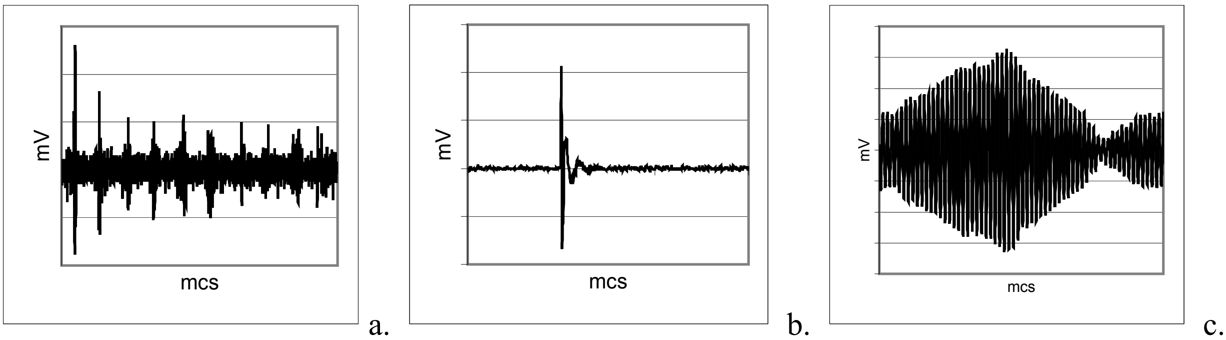

Fig.3. Some types of noise signals a) electromagnetic noise; b) electric noise; c) narrowband harmonic noise

The median filtering can also help in filtering of narrowband amplitude-modulated noises (Fig. 3c); in this case the signal spectrum undergoes the median filtering. The spectrum of such signal has a well-defined single peak which is removed during the median filtering of the signal spectrum (6). Energy of the narrowband quasiharmonic noise decreases by hundreds of times during the spectrum median filtering, while energy of the acoustic emission signal, which has no defined single peaks in the spectrum, varies insignificantly.

$$s(n) = \frac{1}{2\pi}\sum_{i=0}^{N} median(F(\Omega))e^{-jn\frac{2\pi i}{N}} \tag{6}$$

Upon allocation of the desired frequency range in the signal and elimination of the impulse noises, the problem of additive white noise elimination from realizations of the acoustic emission signals remains unsolved. For filtering of additive random noises, the A-Line 32D system employs the wavelet-thresholding algorithm.

The wavelet-thresholding algorithm is performed on the basis of a discrete wavelet-transformation [3]. The acoustic emission signal is represented as a wavelet-decomposition, as a set of detailing and approximation coefficients, which correspond to different scale values (7).

$$s(n) = \sum_{k=-\infty}^{\infty} A_{m',k}\, \varphi_{m',k}(n) + \sum_{m=m'}^{\infty}\sum_{k=-\infty}^{\infty} D_{m,k}\, \psi_{m,k}(n), \tag{7}$$

where $\varphi(n)$ – basic function of sequence of orthogonal embedded subspaces, while $\psi(n)$ – its orthogonal complement.

Representation as a wavelet-decomposition is organic (natural) for a multicomponent signal of acoustic emission, which is a package of different wave modes. Characteristics of separate modes of the wave package are described by the detailing and approximation coefficients.

Fig.4 shows the algorithm diagram. Upon calculation of the wavelet-decomposition, a threshold restriction of the detailing coefficients is performed followed by a signal reverse recovery [4].

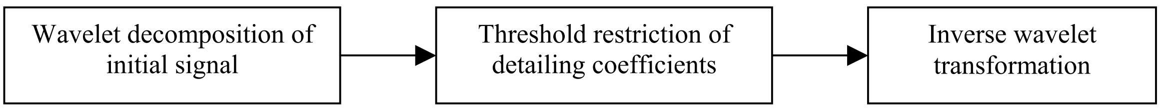

Fig.4. Wavelet thresholding algorithm

Application of the threshold algorithm is equivalent to an adaptive smoothing. When the detailing coefficients readings are put to zero, which correspond to the signal high-frequency components, the signal low-frequency filtering is carried out. On the other hand only the readings, whose fraction of the high-frequency components is relatively smallish, below the threshold, are put to zero; in this case no distortion of the signal fragments, in which the high-frequency component prevails, occurs. Thus, a local selective removal of the high-frequency noise components takes place.

One of key questions is the threshold correct selection. Assume that the informative signal of acoustic emission *f (n)* is observed against the background of the additive noise *(n)*, as a result the sensor measures the signal *s (n)*,

$$s(n) = f(n) + noise(n) \tag{8}.$$

When selecting the threshold optimum value, the risk function equal to mathematical expectation of the norm of difference of functions *f (n)* and function *s (n)* after thresholding is minimized. The criterion of Stein-Stein's unbiased risk estimation (SURE) is the most effective and widespread [5]. The basic advantage of SURE estimation is the fact that it does not depend on the signal type. To calculate the risk function (9), the measured signal *s (n)* and the noise dispersion estimation σ are used only.

$$r(s,f,l) = \sum_{k=l}^{N} sort|s(k)|^2 - (N-l)\sigma^2 + l(\sigma^2 + T^2) \tag{9}$$

Realization of various algorithms of AE data filtering allows for improving the noise immunity of the acoustic emission system as a whole (fig.5). Elimination of impulse noises caused by electric and electromagnetic pickups allows for increasing the measuring channel bandwidth capacity, while elimination of stochastic noise from the acoustic emission signals allows for determining more precisely AE parameters, which can form the basis for authentical determination of the acoustic emission source characteristics.

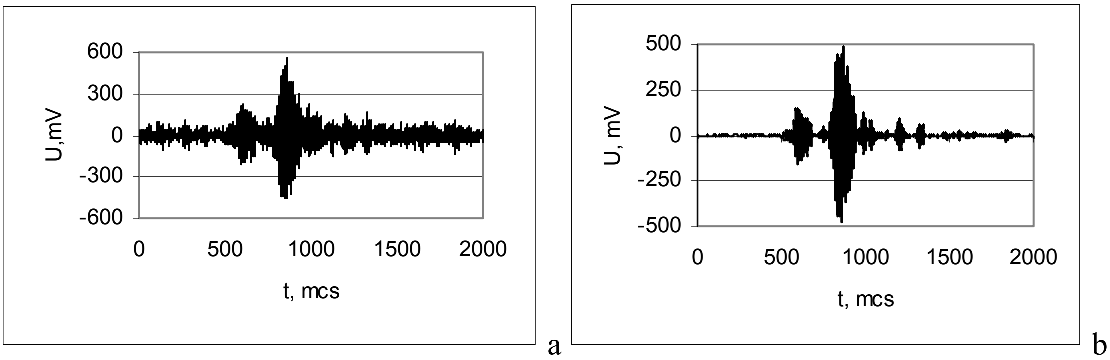

Fig.5 Wavelet thresholding's results: a) initial AE signal b) signal with threshold noise reduction

4. Data Structure and Clustering

In spite of the application of various filtering methods, an amount of AE data to be measured under AE testing and AE monitoring is very large. The large bulk of data hinders processing of initial diagnostic information – acoustic emission signals. The operator will not be in position to process manually dozens or even hundred thousand oscillograms. For AE data processing and structuring the software comprises the algorithm of data automatic structuring [6].

This method makes it possible to process bulk data obtained as a result of the AE testing or during the laboratory research in the absence of *a priori* information. As a consequence of processing, the data are structured and organized; each cluster formed as a result of analysis characterizes an AE source at a definite stage of development.

Our approach is based on the idea that the signals generated by the same AE source have a similar waveform. This similarity may be explained by the similar way of AE wave generation and by the same acoustic path for AE wave propagation. AE waves from the growing defect propagate in all directions. At the sensor location point these waves are registered and transformed into AE signals.

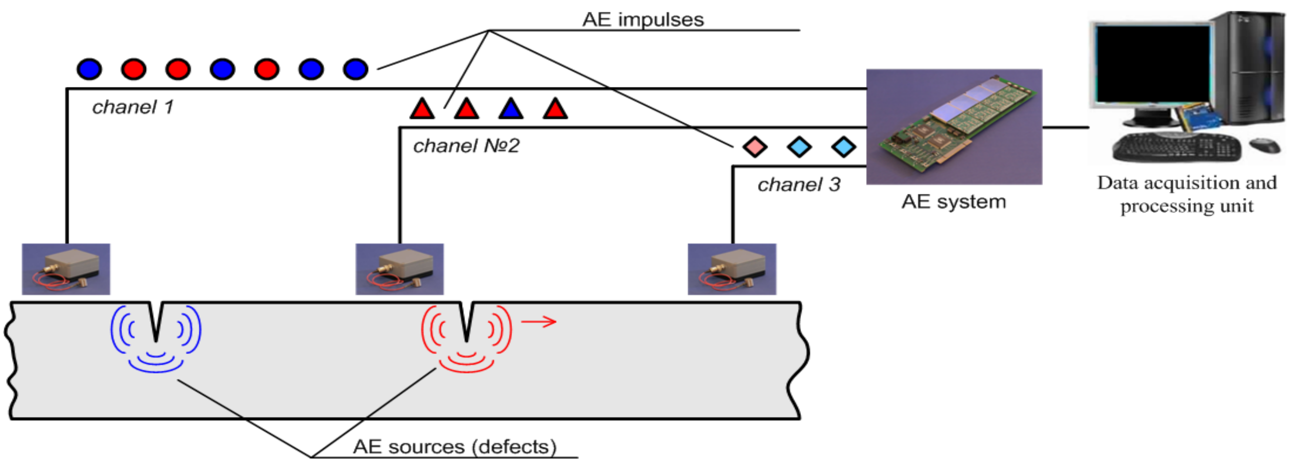

Fig.6. Diagram of recording the acoustic emission impulses from two sources (continuity deffects)

Fig.6 illustrates schematically the process of acoustic emission waves propagation and recording. Two defects of continuity present the acoustic emission wave sources. The wave front of each AE source is marked by an individual color. The acoustic emission signals are shown in Fig. 5 as geometrical figures (circles, triangles and rhombi). The different shapes of figures mean the different measuring channels for which the signals are recorded, while the different colors correspond to the different emission sources.

With the help of signal analysis we simulate the reverse process – signals grouping and unifying. The initial data for algorithm, which realizes this method, can be both the AE signals and their parameters computed under data acquisition in on-line mode. When the processing begins, the initial data represent a bulk of different diagnostic data, at each step of algorithm the data consecutive structuring takes place.

At the first step the signals generated by the same AE event are grouped together. For that purpose we compare the differences in the signals arrival time with the distances between sensors. This group of AE signals is designated in Fig.7 with small figures joined by a brace.

At the second step the groups obtained are classified. Algorithm designed for this purpose has a hierarchical structure. At the first stage AE signals are classified in accordance with the signal waveform similarity. In the diagram different classes of signals are marked with different colors. The groups of signals are classified according to the result of previous classification. The groups, wherein the signals recorded by the same channel have a similar waveform, are assigned to the same class. The classes of groups obtained in this way correspond with a high degree of probability to the potential AE sources.

When a part of AE signals is defined only by parameters, and waveforms are absent, the *"classes of signals"* and *"classes of groups"* are formed on the basis of incomplete diagnosis information. For classification of AE signals specified only by their parameters, each "class of groups" is characterized with a feature set included into the list of impulse parameters to be defined. In this case the classification of AE impulses for which there are no the primary diagnosis data is accomplished on the basis of multidimensional empirical distribution function built for the calculated features.

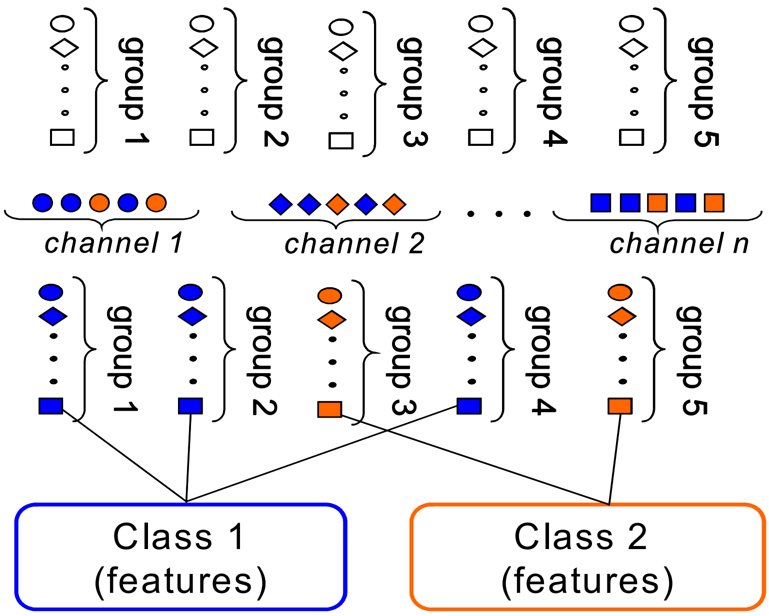

Fig. 7. Flowchart of automated method of AE data analysis.

The basic advantages of this method is, firstly, the possibility to process large bulks of AE data in an automatic mode, with minimum human intervention and minimum number of settings, and, secondly, the possibility to analyze the diverse diagnostic information within the limits of one algorithm.

The statistical analysis results makes is possible to define more exactly a number of acoustic emission sources, carry out their zonal locations, and obtain additional estimations of criteria of each source danger, without resorting to a preliminary location.

5. Location and Thickness Measurements Based on AE Signals Dispersion Propagation Analysis

In 90% of cases the AE testing is carried out on thin-wall objects with the wall of 3-100 mm thickness. In this case the basic energy of AE waves falls within Lamb waves distinguished by a strong dispersion - presence of the frequency dependence of the velocity propagation. Therefore, in spite of the fact that the AE signal is emitted by a microcrack as an impulse of 0.001-0.01 μs length [11], the different frequency components of the signal are recorded by an acoustic emission sensor with a spread of dozens and hundred microseconds, that significantly reduces the source location accuracy.

Under testing the thin-wall objects, for the more exact location of acoustic emission sources the time-frequency representation of signals is effective, which allows for analyzing the AE signal spectrum change with time. Using Fourier-spectrograms, Wigner transformations, wavelet-transformations and other time-frequency transformations [10], the acoustic emission one-dimensional signal is represented as two-dimensional distribution of signal energy in time and in frequency.

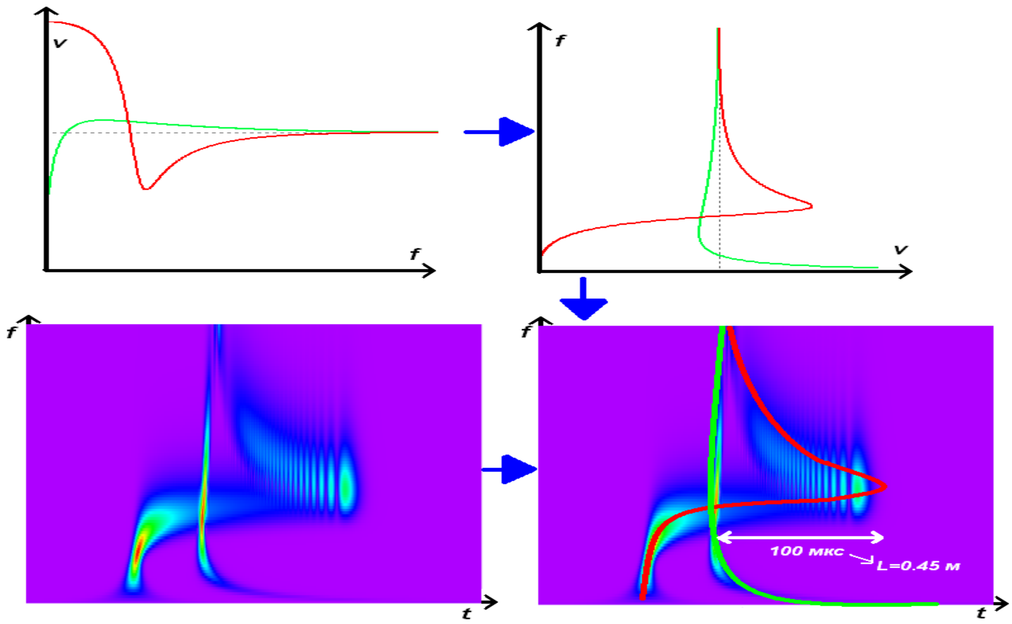

Fig.8 Study of AE signal’s dispersive structure with the help of time-frequency analysis

The signal energy in a time-frequency plane concentrates along lines of dispersion curves relevant to times of different frequencies of AE signal. Each dispersion curve corresponds to its own wave mode. When analyzing the time - frequency signal distribution, it is possible to detect the lines relevant to the dispersion curves and estimate the signal dispersion structure. Fig. 8 shows an example of such processing. In the display which corresponds to the time-frequency transformation of AE signal (Fig. 9a) the lines of different orientation are highlighted, and using piecewise-linear approximation the dispersion curves (Fig. 9b) are restored and their characteristic parameters are defined (Fig. 9c).

The analysis of the dispersion signal structure allows to restore (redesign) the parameters of acoustic emission wave front propagation, and to determine the acoustic path characteristics, such as the test object wall thickness, defects location and their occurrence depth.

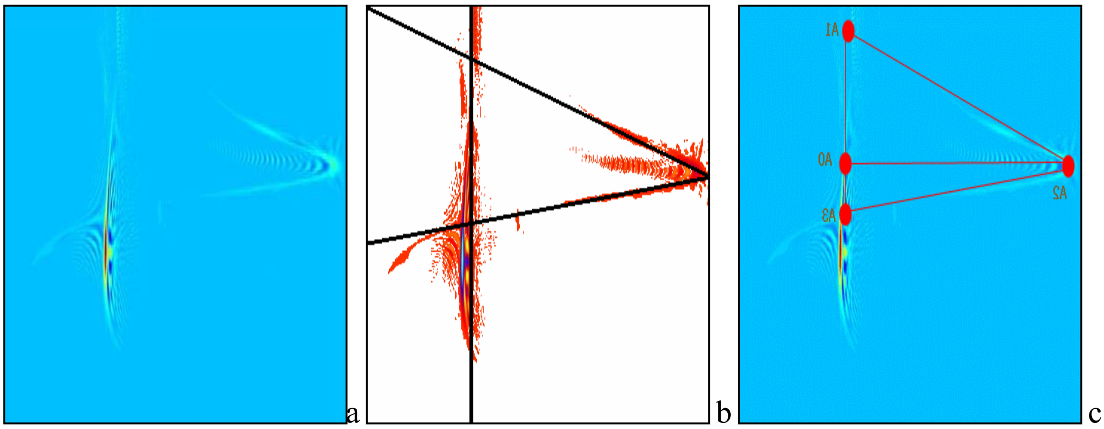

Fig.9 Detection of dispersion curves at time-frequency transformation of AE signal

The software of A-Line family systems represents calculation of different time-frequency transformations and algorithm of the signal analysis dispersion structure. Implementation of these algorithms allowed to significantly expand the system functionality, most of all, due to the possibility to perform integrated measurements of thickness.

The velocity of Lamb waves propagation depends not only on the frequency, but also on the test object wall thickness. As the material undergoes degradation, the test object walls become thinner, thereby changing the acoustic path characteristics. An integrated value of the test object wall thinning can be judged from change in the propagation dispersion pattern.

The acoustic thickness measurements, in contrast to the classical acoustic emission testing, is an active method and requires the stimulation by Xcy-Nilsen simulator or piezoelectric sensor situated from the sensor at some given distance. A large body of experimental research has shown that the determination accuracy of integrated thickness is 1-3%. In this case the size of area under testing can vary from 10 up to 50 meters depending on stimulation characteristics.

6. Approximate Location by Free-Form Sensor Array (ALFS).

The precision method of "fuzzy" location is an automated and reliable high order localization algorithms. The backbone of the suggested method is an assignment of a range (or several ranges) of velocities containing the velocities of basic modes of elastic waves on the structure. The AE source location is calculated on the principle that the wave velocity, whose the front arrival time is recorded by each of the sensors, lies within the selected velocity range.

Under description of this location method it is convenient to use the concept of “impulse group”: some population of AE impulses recorded by various sensors, during one act of acoustic emission.

The ALFS method consists in calculating for each such “impulse group” the object region comprising all possible points where the event could be capable to generate this “impulse group”at the given arrangement of sensors and the given velocity range of elastic wave propagation over the object surface [13]. For this purpose the object surface is modeled with a discrete mesh of finite number of points. For each “impulse group”, the ALFS method calculates all nodes of this mesh, near which the given AE event could theoretically occur. The list of all such nodes is the location region description for the given “impulse group”.

The location is approximate because for each “impulse group” not one point on the object is indicated, but a region. However, the calculation of a single location point is impossible without an error. This approximate method is more accurate than the point location, since the desired source of event is within the obtained region with a high probability. Intersection of the location regions obtained for the different “impulse group” allows the source to be located more precisely, provided that the several “impulse group” of signals have been received from the same source as a result of the several discrete AE events. When the object regions are displayed in A-Line program the overlay sections of location regions are different in color depending on how many regions are overlapped on this section.

The size of the region thus determined can be reduced and so the accuracy of source locating can be additionally increased by the following several methods: proved reduction of the selected range of elastic wave velocities, selection of the optimum sensor number for calculating each region of the source location, for some sensors the velocity ranges of acoustic waves can be specified individually.

To obtain the best results, the operator can change all the above-mentioned parameters of the method on-line. Figure 10 shows results of ALFS implementation compared to the classical triangulation location method on the cylindrical tank surface.

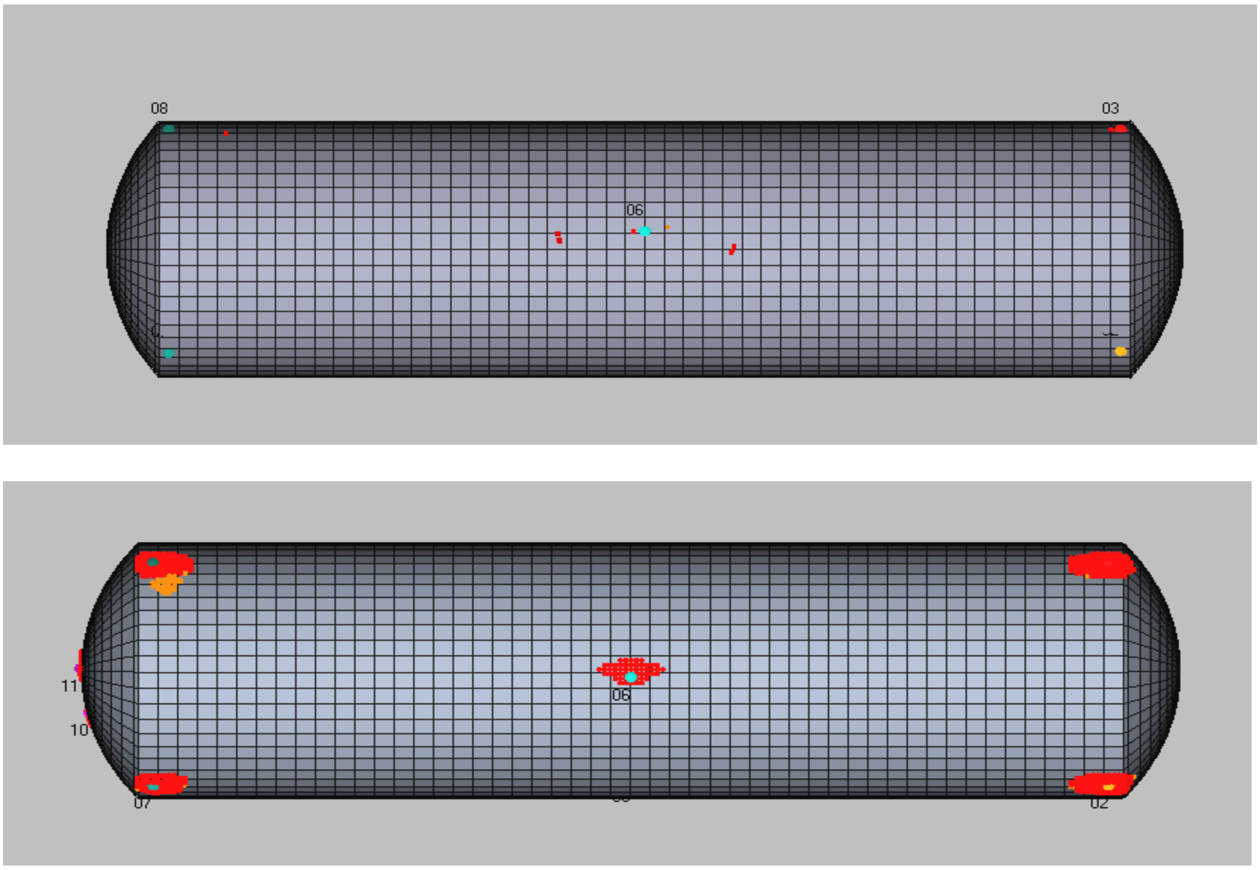

Fig.10 Results of ALFS implementation (two lower pictures) compared to the classical triangulation location method (two upper pictures) on the cylindrical tank surface.

7. Conclusion

In this paper described are methods of the intelligent data processing used at all stages of acoustic emission testing – at calibration measurements, in the course of data acquisition, and at delayed analysis. All methods and algorithms described above are presented and implemented in the A-Line 32D system software (Interunis company) [16].

Implementation of the intelligent data processing methods has allowed to make the AE system more functional, the testing results more reliable, and also to organize the measuring process more friendly to an operator. As all data processing algorithms are automated, increase of research intensity of AE system imposes no additional requirements to qualification of the operator, who conducts the nondestructive testing.

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