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DEVELOPMENT A MATHEMATICAL MODEL OF ACOUSTIC SIGNALS FOR THE IMPLEMENTATION OF A UNIVERSAL LEAK DETECTION METHOD

O. Monchenko
PhD, Associate Professor
Department of Biocybernetics and Aerospace Medicine*
E-mail: monchenko_olena@ukr.net

Y. Kutniak
Postgraduate Student
Department of Engineering, Standardization and Certification*
E-mail: mazurenko.liza@gmail.com

H. Martyniuk
PhD
Department of Information Security*
E-mail: ganna.martyniuk@gmail.com

N. Marchenko
PhD, Associate Professor
Department of Computerized Control Systems*
E-mail: nadmar@i.ua

*National Aviation University
Liubomyra Huzara ave., 1, Kyiv, Ukraine, 03058

Представлено універсальну математичну модель шумового сигналу в трубопровідних системах від місць їх виникнення до точки спостереження. За рахунок введеної в неї індикаторної функції модель дає можливість в залежності від поставленої задачі використовувати різні типи компонент і виконувати з ними відповідні дії, а індикаторна функція в окремих випадках буде дорівнювати нулю.

Метою розробленої моделі є те, що вона є універсальною для методів течошукання, які використовують два приймачі сигналу незалежно від їх фізичної природи. В статті така модель реалізована на прикладі методу акустичного течошукання, що використовує взаємокореляційну функцію. Наведено структурну схему акустичної системи виявлення місця витоку, основні блоки та їх параметри. Для перевірки працездатності математичної моделі проведений комп'ютерний вимірювальний експеримент в середовищі Matlab. Наведено алгоритм комп'ютерного експерименту з урахуванням індикаторної функції та наведено результати пошуку місця витоку за відповідною вибіркою.

Запропоновано універсальну формулу обрахунку координати місця витоку рідини з трубопроводу як вздовж осі трубопроводу, так і за діаметром трубопроводу. Особливістю формули є те, що в ній враховується відстань від перетворювача до можливого місця витоку з урахуванням номера вибірки. Представлена формула обслуговує універсальну модель шумового сигналу та підтверджує результати комп'ютерного експерименту.

В результаті експерименту отримані залежності значень місця витоку рідини від номера вибірки та відстані до приймача акустичного шумового сигналу. Для перевірки моделі на адекватність побудовано діаграму впливаючих факторів у вигляді діаграми Ісікави. Діаграма показує причинно-наслідкові зв'язки, що впливають на роботу комп'ютерного експерименту, побудованого на основі запропонованої математичної моделі акустичних сигналів для реалізації універсального методу течошукання. Адекватність запропонованої універсальної моделі перевірена та підтверджена статистичними методами.

Отримані результати можуть бути використані для технічної діагностики трубопроводів та щодо зниження витрат на ремонт і відновлення технологічних систем шляхом виявлення місць пробою

Ключові слова: акустичний сигнал витоку, універсальна математична модель шумового сигналу, комп'ютеризована система виявлення місця пошуку течі

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1. Introduction

The reliability and efficiency of thermal power equipment and systems are largely determined by the state of their pipelines. Disturbance of the working capacity of water and heat supply systems caused by the failure of their elements causes losses for the economy, environment, and worsening of working and living conditions [1]. Methods and means of functional diagnostics based on various physical phenomena and principles have the greatest prospect for detecting leaks and locating pipeline damages without decommissioning of pipelines. Each of them has its own implementation means.

Analysis of modern methods of detecting and locating leaks has shown that acoustic contact methods of controlling pipeline leakage have great potential. However, their application is often accompanied by significant errors in leak detection. This is caused by the design of the test object which is not always simple, ambiguity of physics of leakage signal formation in through defects of the test object and presence of interferences. Interference is caused by the propagation of leakage signals or other processes occurring in working test objects.

Despite a large number of solutions in this field, their application is often accompanied by significant errors in leak detection. This is determined by not always the simple design of the test object, lack of direct access to the leaks, complex probabilistic nature of acoustic signals of leakage. This is also caused by the ambiguity of the physics of the formation of leakage signals in through defects of the test object and presence of interferences that occur in leakage signal propagation or is brought about by other technological processes of the working test object.

Capabilities of leak detection methods are determined not only by the method of generation of information signals in the "converter – test object" system but also by the chosen data parameters and signal characteristics and the search for a universal processing method.

2. Literature review and problem statement

Study [1] describes methods and procedures of leak detection based on various physical phenomena and principles such as pressure monitoring by means of fixed or sliding devices, method of scanning waves, negative shock waves, comparison of cost, change of flow rate and linear balance.

Each of the above methods has its advantages and disadvantages. The method of acoustic contact leak detection is the closest in the technical sense. It is based on an analysis of the characteristics and parameters of acoustic signals of leakage. Signals are recorded using transducers having direct contact with the wall of the test object. It should be noted that signals are analyzed using the methods applicable only for analysis of stationary acoustic signals, and the fact that signals can be non-stationary is not taken into account. The main features of the leak detection means include location accuracy and remote control.

Most known devices and systems of acoustic leak detection are based on correlation analysis of acoustic signals of leakage. The principle of these devices consists of measuring the time delay of the maximum value of the inter-correlation function between the acoustic signals recorded by two spaced receiving transducers [2].

Distance from a leak to one of the transducers is calculated from the following formula

$$l = \frac{L - \tau_0 c}{2}, \quad (1)$$

where L is the distance between converters; c is the speed of propagation of acoustic signals in a pipeline (specified or measured); τ_0 is the difference between time durations of the passage of acoustic signals from leakage to each of the transducers. The value of τ_0 is determined by the inter-correlation function of signals from sensors "a" and "b":

$$R_{ab}(\tau_0) = \max_{\tau}\left(R_{ab}(\tau)\right). \quad (2)$$

Capability to record low-level signals with low- and high-frequency components is the main requirement for sensors.

The development of acoustic contact leak detection requires further study of the physical processes of acoustic signal generation by the leak [3].

The study [2] is devoted to finding an optimal method of detecting fluid leakages based on a comparison of the commercial methods used today. However, it should be noted that the results of the choice of an optimal method are based only on the review of published studies with limited quantitative data. If more accurate data will be found on acoustic methods of detecting fluid leaks, then this optimum method may change.

A mechanism of leakage source generation in gas-liquid two-phase pipelines is analyzed in [3]. Acoustic analysis was performed using empirical mode decomposition. These studies formed the basis for the further study of the propagation of acoustic leakage of signals and their positioning for other types of pipelines not described in the paper.

A method for locating leaks in pipelines is proposed in [4]. Two sensors of body noise are installed in two accessible places of land pipelines so that there is an expected leak between them. The leaking media distort stochastic noises. Noise signals propagate through the pipeline to the sensors. These signals are subjected to correlation. The difference between the two values of the delay time is found from the inter-correlation function (ICF) and hence, the leak location as well.

It is important to note that the capabilities of correlators depend on pressure and background noise in the network. There is also no data on the accuracy of determining the leak location.

To analyze the process of propagation of acoustic waves, it is necessary to pay attention to the model of these acoustic waves first of all. When constructing a model, much attention is paid to the uniform distribution law since any signal model can be created on its basis. In study [5], attention is paid to the criteria of sampling verification for belonging to the uniform distribution law. However, it rather poorly describes the results for short implementations which can be used as intervals for stationarizing the noise signals.

To implement the universal method of leak detection, it is necessary to use combined diagnostic systems that make it possible to determine with high probability current state of the pipeline. For example, it was demonstrated in [6] that pipeline networks of pumping systems are characterized by a high degree of breakdown by leakages accompanied by complex wave processes in the hydraulic system. It was found that the wave processes of the network pipelines depend on location and amount of leakage, structural parameters of the hydropower network, and properties of the fluid being transported. However, in this case, it is suggested to use only the hydraulic power signal to identify the leakage location.

Currently, the rise in prices of new spare parts on the one hand and the requirement to reduce operating costs on the other hand while maintaining the level of reliability and safety necessitates the system improvement. In [7], attention is focused on assessing the reliability of pipelines throughout the life cycle. In addition, a study of poor repair impact on forecasting the reliability of such a pipeline is carried out. It should be noted that the experimental part is based solely on the use of Poisson distribution.

Methods used to test pipeline performance in various fields of technology [8] or functional diagnostics based on various physical phenomena and principles [9] make it possible to determine the pipeline performance at the time of inspection. This approach was used in [9], however, it is impossible to reliably find the location of pipeline damage without its decommissioning when using these diagnostic parameters.

Mathematical models of signals with low resolution were considered in [10]. Graphs of time realization of signals in the model, spectra of realized signals as well as their autocorrelation functions reflecting main characteristics of signals at the point of measurement were presented in [11] for stationary cases. It should be noted that basically every study is aimed at the analysis of certain kinds of signals and the model of such a signal is presented differently in each study.

Thus, the review of current scientific solutions [1–11] has shown a wide range of applications of leak detection methods. However, the practical implementation of such methods has some limitations and is not always acceptable.

Some elements of the proposed solution are known and used in different subject areas but their totality, a universal mathematical model of the noise signal, and a computer experiment for its implementation which would be satisfied by the methods that use signals of different physical nature were not used. The review of the published data has shown once again the need to address the leakage problem and improve the accuracy of leak detection.

3. The aim and objectives of the study

The study objective is to develop a universal mathematical model of the noise signal as a component of leakage detection methods that use fields of various physical nature.

To achieve this objective, the following tasks were set:

– to include additional operations of noise signal analysis in the acoustic leakage detection method that uses ICF;

– to conduct a computer experiment of leak location;

– to derive a formula for calculating leak location.

4. Construction of a universal mathematical model of acoustic signals

The acoustic method of leak detection based on the use of the inter-correlation function was used as a basis and the process of formation of acoustic leakage signals was studied.

The acoustic signal model has long been known and is commonly used in practice as a stationary signal. But it should be noted that usually, the acoustic signal may not be completely stationary. For example, it was already considered in [6] as a non-stationary signal which is difficult to implement in modeling. A solution may consist in presenting the acoustic signal as a piecewise stationary signal because intervals of stationarization can be found in some short periods.

In order to describe all possible variants of noise signal generation, a universal noise signal model has been constructed that can be used for mathematical and computer modeling as a three-component vector random process of the following form:

$$\Xi_3(t)=\left({}_1\xi(t),\ {}_2\xi(t),\ A(t)\right),\ \ t\in T. \tag{3}$$

The following was used as components of the random process (3):

1) component

$${}_1\xi(t)=\sum_{i=1}^{n}{}_1\xi_i(t)I(t,\Delta T_i),$$

where $\left\{{}_1\xi_i(t), i=\overline{1,n}\right\}$ is the sequence of random stationary linear processes;

2) component

$${}_2\xi(t)=\sum_{j=1}^{m}{}_2\xi_j(t)I(t,\Delta T_j),$$

where $\left\{{}_2\xi_j(t), j=\overline{1,m}\right\}$ is the sequence of harmonizing processes;

3) component

$$A(t)=\sum_{l=1}^{k}A_l(t)I(t,\Delta T),$$

where $\left\{A_l(t),\ l=\overline{1,k}\right\}$ are the approximating functions of the measurement data at the realization of a random variable $\xi(t_0)$;

4) the indicator function is given by

$$I(t,\Delta T_j)=\begin{cases}1, & t\in\Delta T_j\\ 0, & t\notin\Delta T_j,\end{cases}$$

and formed in practice by instantaneous time moments of disorder of homogeneity of the components under study, in other words, by intervals of homogeneity

$$[0,\Delta T_1)\cup[\Delta T_1,\Delta T_2)\cup\ldots\cup[\Delta T_{n-1},\Delta T_n]=[0,T]$$

of the components under study.

The versatility of this model is achieved due to the fact that it is unnecessary to use all components of the random process simultaneously. This can be achieved by means of an indicator function which will be zero in some cases. In addition, the three components can be combined in different ways: they can be added, subtracted, multiplied, etc. for different signal models.

If leakage occurs at some point x_0 of the diagnosed object because of pressure drop, the working fluid leaks from the pipe. This leads to the generation of an acoustic leakage signal $\xi_{leak}(t)$, that propagates through the pipeline on both sides of the point x_0 and is detected by transducers (sensors) installed at the points x_1 and x_2 of the pipe.

In a general case, the signals $\xi_1(t)$ and $\xi_2(t)$ at the outputs of electroacoustic transducers EAT1 and EAT2 differ from the leakage signal $\xi_{leak}(t)$, Besides, the transducers record acoustic interferences $\xi_{int1}(t)$, $\xi_{int2}(t)$, caused by the noise generated by fluid flow and the receiving and recording equipment (Fig. 1).

In a general case, leakage and interference signals $\xi_{leak}(t)$, $\xi_{int1}(t)$, $\xi_{int2}(t)$, are non-stationary because they depend on pressure in the pipeline and the heat carrier temperature. However, these signals can be considered stationary in short time intervals (about several minutes) required for processing.

In addition, it should be noted that when considering signals at the intervals of stationarization, interference signals can be represented as stationary linear signals of random processes and acoustic signals of leakage as periodically correlated random processes which is a partial case of non-stationary harmonizing processes.

The signals $\xi_1(t)$ and $\xi_2(t)$ at the output of transducers are described by the following expressions:

$$\xi_1(t)=A_1(t)\xi_{leak}(t-\tau_1)+\xi_{int1}(t),$$

$$\xi_2(t) = A_2(t)\xi_{leak}(t-\tau_2) + \xi_{int2}(t),$$

where $\xi_{leak}(t)$ is the acoustic signal of the leak; $\xi_{int1}(t)$, $\xi_{int2}(t)$ are the acoustic signals of the transducer interferences; $A_1(t)$, $A_2(t)$ are the approximating functions of measurement data that correspond to amplitudes of acoustic signals; τ_1, τ_2 are the delays of the arrival of the leakage signal to the points x_1 and x_2.

In order to determine the location of liquid leakage in the pipeline, the study proposes the block diagram shown in Fig. 1.

EAT1 and EAT2 convert acoustic signals at measurement points into electrical signals that are fed to the pre-connected charge amplifiers (*CA*). Further, the signals are transmitted through the communication line to the bandpass filters (*BF*) which pass only medium frequencies and then to the processing module of the correlometer. The processing module performs the two-channel analog-to-digital conversion and transmits digitized signals through the port to the calculator (*C*) to which distance (*L*) between the EAT and the leak point and speed (υ) of the leak signal passage are also fed. It performs software processing of signals to obtain temporal and spectral analytic functions, in particular, the inter-correlation function which makes it possible to detect the fluid leakage location. Graphs of the inter-correlation function are displayed on the display (*D*).

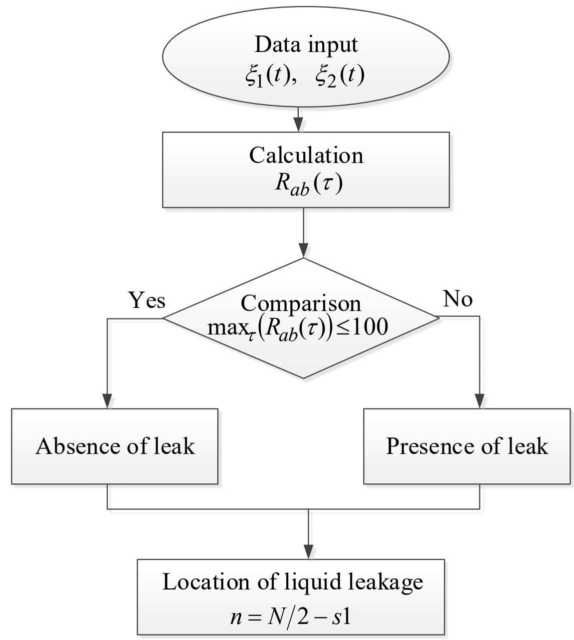

Fig. 2. The algorithm of determining leak location in the pipeline

In this case, meeting the following condition is the criterion for leakage presence:

$$\max_\tau\left(R_{ab}(\tau)\right) \le 100,$$

where $\max_\tau\left(R_{ab}(\tau)\right)$ is the maximum value of the inter-correlation function determined by the acoustic signals $\xi_1(t)$ and $\xi_2(t)$, read from EAT1 and EAT2.

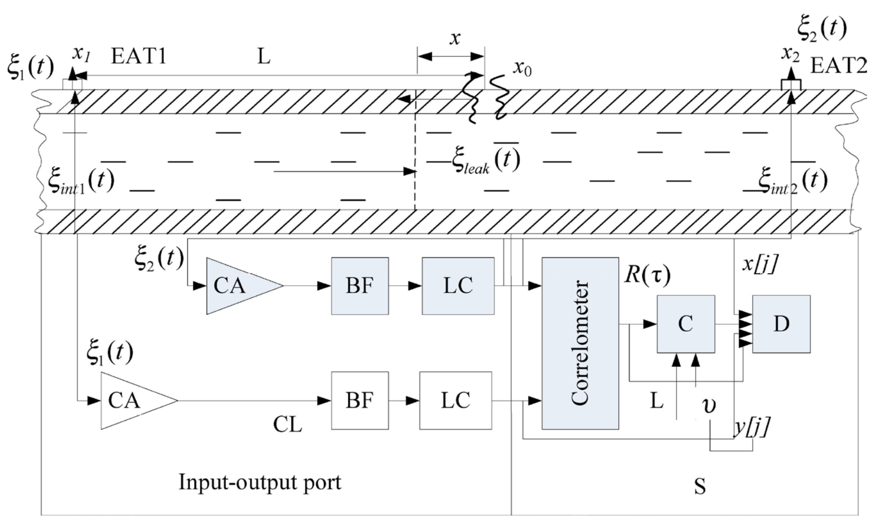

Fig. 1. Block diagram of an acoustic system for leak detection;
CL — communication line; CA — charge amplifier;
BF — bandpass filter (only medium frequencies are passed); LT — linear transducer;
C —calculator; D — display; S — software;
EAT1, EAT2 —electroacoustic transducers;
L is the distance between the EAT and the leak location;
υ is leakage signal pass speed

When fluid leakage takes place, an acoustic noise signal is emitted in the pipeline. Let there be two noise signals received by piezo sensors acting as accelerometers with one signal shifted relative to the other by a delay τ [3].

The use of Gaussian linear random processes as one of the components of the noise signal is connected with the following circumstances:

– Gaussian random processes are uniquely specified by a matrix of correlation moments, so modeling them in a framework of the correlation theory is tantamount to modeling by specified multidimensional distributions;

– modeling of non-Gaussian random processes is reduced to the modeling of Gaussian random processes with subsequent reproduction of the specified transformation for which it is sufficient to provide only the necessary correlation connections of the original (Gaussian) processes;

– multidimensional laws of distribution of non-Gaussian random processes are difficult to obtain theoretically and experimentally. Their correlation moments are usually determined much easier.

5. Computer experiment with leak detection for the universal leak detection method

The computer experiment was performed according to the block diagram given in Fig. 1. The algorithm of determining the location of the pipeline leak is shown in Fig. 2.

Therefore, in these cases, multidimensional laws of distribution are usually unknown, and the task of modeling random vectors is only meaningful within the framework of the correlation theory [12].

Noise signal caused by fluid flow was generated using an array of random numbers according to Gaussian distribution (amount N=100). Thus, the signal (Fig. 3, *a*) received by the accelerometer 1 was obtained. The signal received by the accelerometer 2 was shifted by 100 (Fig. 3, *b*) and ICF was determined (Fig. 3, *c*). The maximum value of the correlation function and its corresponding sample number were then found. The sampling number was the location of the fluid leakage in the pipeline. Modeling was performed in the MATLAB system. Modeling results are presented in Fig. 3.

Therefore, n=40 and is the location of fluid leakage in the pipeline.

There are also cases where it is impossible to determine exactly where a leak will occur in the pipeline, i. e. the leak location is unprogrammable. In this case, the use of the indicator function is suggested.

Then ICE signals from the first and second accelerometers will take the form Fig. 4.

Suppose that the metal wall of the pipeline is a good conductor of acoustic vibrations. Therefore, the acoustic signals of leakage were read from the pipeline walls. Since coordinates of the leak occurrence are unknown, piezoelectric accelerometers can be installed on the pipeline in a different way, both along the pipeline axis and on the pipeline diameter.

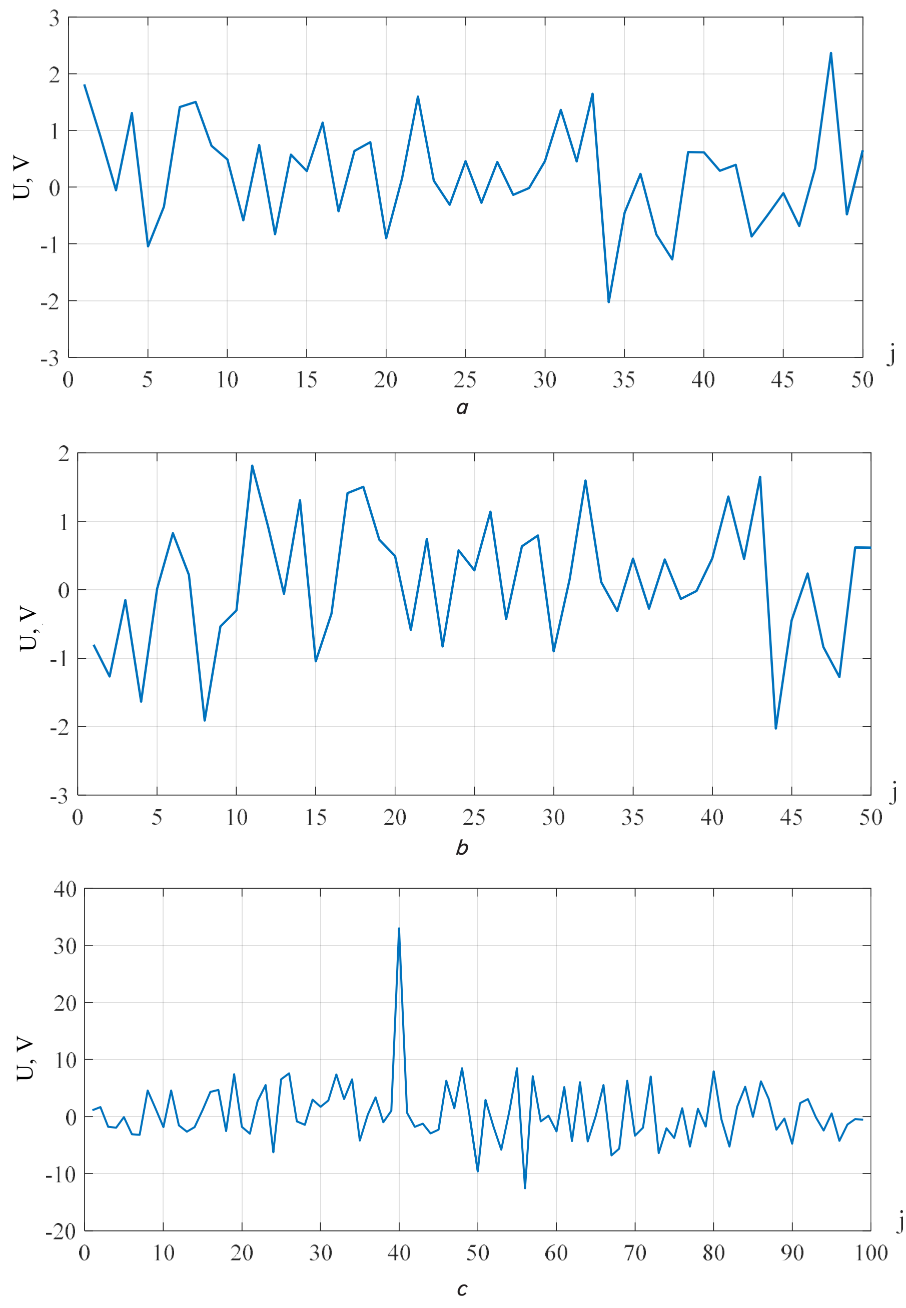

Fig. 3. Determination of the fluid leakage location in the pipeline: *a* – signal from the first accelerometer; *b* – signal from the second accelerometer; *c* – inter-correlation function of signals from the first and second accelerometers

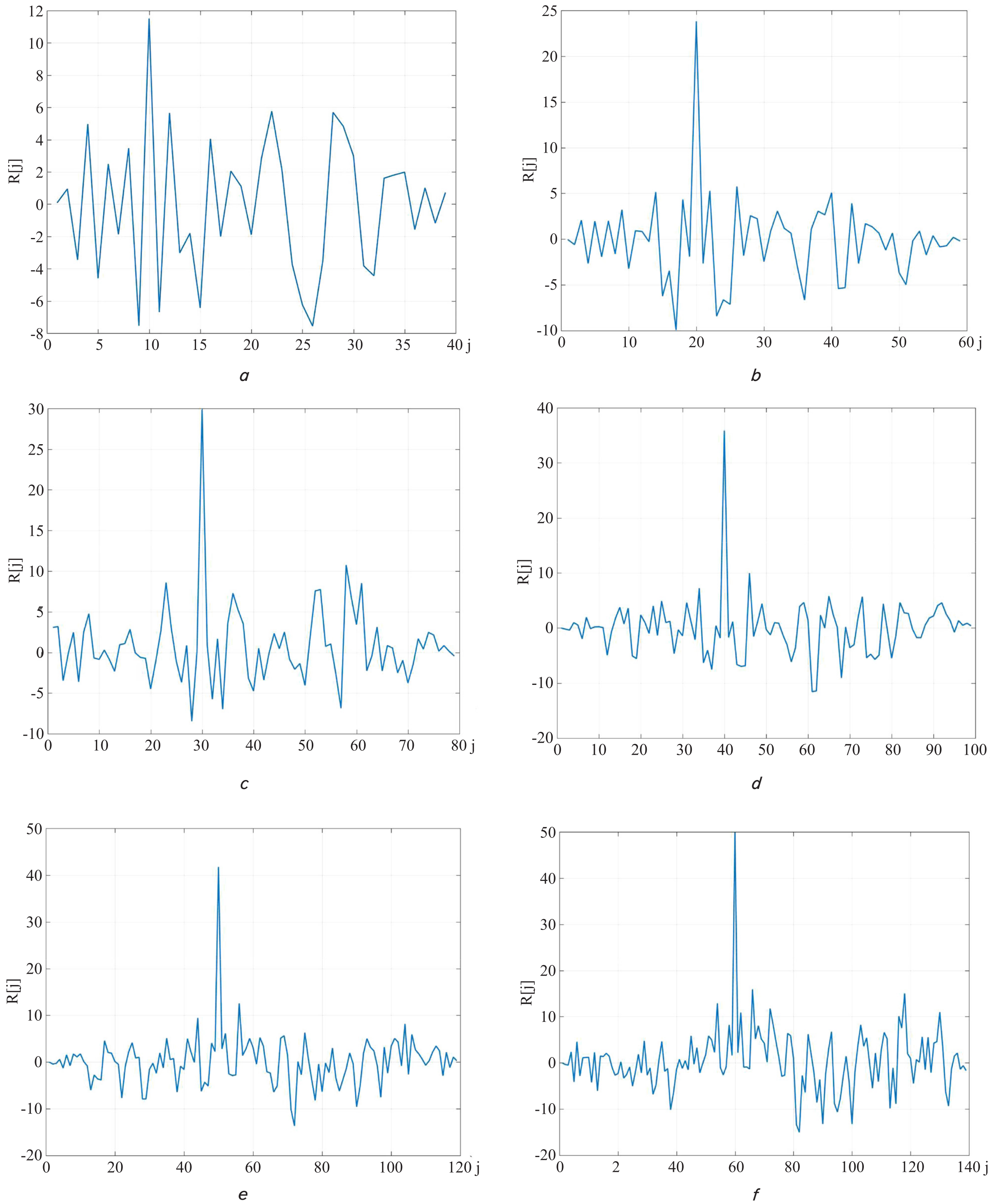

Fig. 4. Determination of the fluid leakage location in the pipeline: *a* — location of the leak occurred at *n*=10 ; *b* — leak occurred at *n*=20; *c* — leak occurred at *n*=30; *d* — leak occurred at *n*=40; *e* — leak occurred at *n*=50; *f* — leak occurred at *n*=60

6. The formula for leakage calculation and check for the model adequacy

A procedure of determining the exact location of fluid leakage in a pipeline was developed. For this purpose, a conditional scheme of accelerometer installation to determine leakage location was worked out (Fig. 5).

When comparing mean square deviations (MSD) of two acoustic signals EAT1 and EAT2 in the position of the largest MSD, it is likely that the accelerometers took position on the same line with the leak location:

$\sigma_1 = 0.7869$ m/s^2,

$\sigma_2 = 0.5367$ m/s^2.

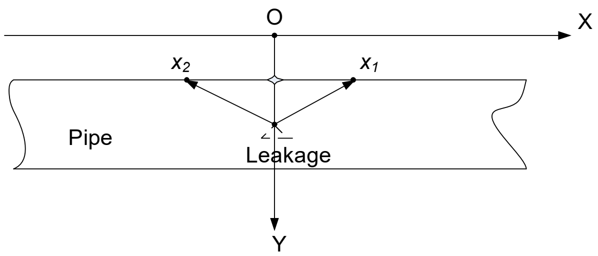

Fig. 5. Installation of accelerometers on the pipe

It follows from the results that MSD at the point x_2 is less than the MSD at the point x_1. Therefore, in subsequent studies, the leakage signal will be read only at the point x_1.

The modeling results were converted into time parameters: sampling rate of ADA-1406 LT is 350 kHz. Acoustic signal sampling step:

$$\Delta t_d = \frac{1}{f_d} = \frac{1}{350 \cdot 10^3} = 2.8 \quad (\mu s).$$

Time delay of the signals is determined by taking into account the shift and location of the piezoelectric accelerometers along the pipe diameter:

$$\Delta t = n \cdot \Delta t_d,$$

where n is the sampling number.

The shift occurs until the delay time of the acoustic signal is shortest. At the same time, the accelerometer should not be on the same line with the fluid leakage point.

Therefore, depending on the sample number, step of the acoustic signal sampling was 28 µs when n=10; 56 µs when n=20; 84 µs when n=30; 112 µs when n=40; 140 µs when n=50; 168 µs when n=60 and 196 µs when n=70.

The following formula was used to calculate the distance between a possible fluid leak location and the center C between EAT1 and EAT2:

$$\frac{\Delta l}{2} = \frac{V \cdot \Delta t}{2}, \qquad (4)$$

where V is the speed of sound in a metal pipe; V=5,000 m/s. Distance between the piezoelectric accelerometers was L=1 m and the distance from the center O was 0.5 m.

Therefore, depending on the sample number, distance between the possible leakage site and the center point between the piezoelectric accelerometers is 0.07 m at n=10; 0.14 m at n=20; 0.21 m at n=30; 0.28 m at n=40; 0.35 m at n=50; 0.42 m at n=60; 0.49 m at n=70. The calculated accuracy is approximately 1 cm, which is an order higher than in existing systems.

Thus, it is necessary to derive a rule of determining acoustic signals of a pipeline leak based on the physics of such signals and their mathematical model in order to minimize the error of signal missing.

Measurement errors are the main quality characteristic [9]. Fig. 6 presents a structured graphical representation of a set of factors in a form of Ishikawa diagram affecting the passage of fluid flow in a pipeline.

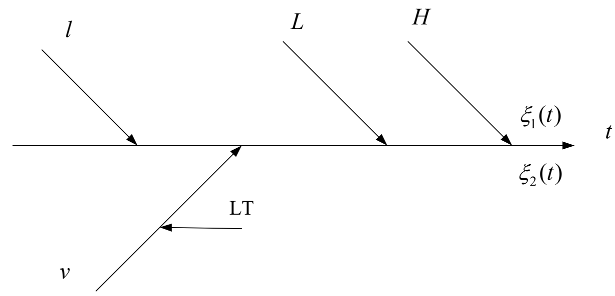

Fig. 6. Ishikawa diagram

Thus, the following factors influence the time of passage of fluid flow in a pipeline:

– l: distance between the piezoelectric accelerometer and the fluid leakage location;

– L: distance between two piezoelectric accelerometers;

– H: pipe wall thickness;

– υ: speed of the leakage signal passage along the pipe;

– acoustic signals $\xi_1(t)$ and $\xi_2(t)$, read from piezoelectric accelerometers;

– bit size of the LT.

Since the model experiment was conducted in the study, i. e. random variables distributed according to the Gaussian distribution law were used, it is necessary to check the data for correctness and validity.

The modeling results obtained in the study were checked according to Pearson's criterion of consistency [8]. It was found that the distribution of random quantities in the array obeys the Gaussian law of distribution indicating the validity of the modeling results, Fig. 7.

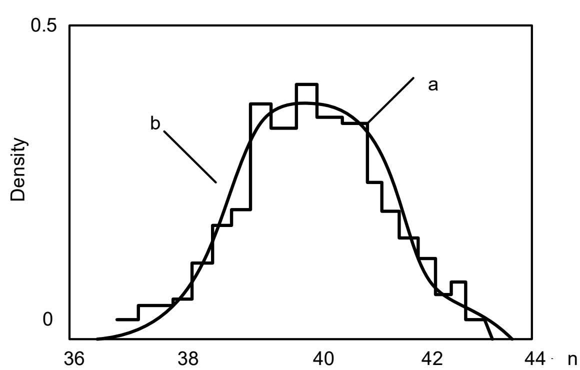

Fig. 7. Pearson's consistency criterion: *a* — histogram of density of distribution of an array of random quantities; *b* — Gaussian law of distribution

It was established by corresponding calculations that the value of the *Xi*-square criterion at the level of significance $\alpha = 0.05$ was 447.17 and the tabular value of the criterion was 500.

Based on the calculated data, a conclusion can be drawn that $\chi^2_m \le \chi^2_{cr}$, at $\alpha = 0.05$, that is, the hypothesis H_0 is accepted. This means that the hypothesis at this level of significance does not contradict the assumed type of distribution which indicates the validity of the modeling results.

Therefore, analysis of the modeling results according to Pearson's criterion of consistency, distribution of random quantities in the array obeys the Gaussian law of distribution which confirms the validity of the modeling results.

7. Discussion of results obtained in modeling the detection of acoustic signals of leakage

Leak detection tasks do not lose their relevance all over the world. Considering the variety of such methods, this study proposes a universal mathematical model of a noise signal that can be used for mathematical and computer modeling as a three-component vector random process (3). Its versatility consists in that one can use not all components of a random process simultaneously. For different signal models, the three components can be combined in different ways: they can be added, subtracted, multiplied, etc. For this purpose, an indicator function was introduced into the mathematical model. The universal mathematical model was tested in a computer experiment. The experiment results are presented in Fig. 4, which illustrates the operation of the indicator function. To find the coordinate of the leakage location, a calculation formula (4) was proposed. It makes it possible to determine the leakage location both on the pipe circumference and the axis. The model was tested for adequacy by statistical methods (Fig. 7).

The universal mathematical model and the developed software can be used for other methods of leak detection using two signal receivers of any physical nature.

The study limitation consists in the fact that it is not always possible to install an accelerometer on a pipeline as there may be no access to the pipe. Therefore, pipelines can be diagnosed in the future by using means of technical testing another type, for example, probes, not accelerometers.

One of the ways to further development of the proposed model is the use of a single transducer to detect leak locations since all current methods use at least two receivers installed around the intended leakage location [1–11].

The results obtained can be used for technical diagnostics to reduce the cost of pipeline repair and restoration by identifying damage locations.

8. Conclusions

1. An indicator function was included in the acoustic leakage method using ICE. The indicator function makes it possible to select the desired component from the noise signal: a stationary linear random process, a harmonized process or approximating functions of the measurement data in realizing the random quantity $\xi(t_0)$.

2. A computer experiment was realized to confirm the model performance. By means of the indicator function used in the mathematical model, a component necessary for this task was selected. In the studies, the signal amplitude was chosen as this component. The sample number was determined by the peak value of the amplitude and, as a consequence, the location of the pipeline damage. The proposed model was tested for Pearson's criterion of consistency. Calculations have determined that the value of the *Xi*-square criterion was 447.17 at the significance level $\alpha = 0.05$ with a table value of 500 which thus confirming the model adequacy.

3. Depending on the sample number, a formula for calculating the leakage location on both the pipeline diameter and the axis was developed. The formula includes distance between accelerometers, speed of the fluid flowing through the pipe, time of delay of the signal containing the sample number. The estimated accuracy was approximately 1 cm which is an order of magnitude higher than in existing systems.

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