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Parametric Analysis of Correlation Functions for Acoustic Monitoring and Assessment of Underground Piping at NPPs

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Monitoring and assessment of the technical condition of underground pipelines of process systems important to safety is a relevant task of the ageing management process for existing NPPs. Methods applied in other industries having underground pipelines (oil/gas/public utilities) could be considered. The paper is devoted to theoretical issues of overcoming the interfering redundancy contained in the mutually correlated functions of the acoustic method for inspection of underground pipelines. The method has been tested in intensive leak inspection of urban heating pipelines and potentially could be beneficial for detecting leaks in the early stages of their occurrence in underground pipelines of the essential service water system at NPPs.

Keywords: coordinate, correlation, interference, leak detection, parametric, pipeline.

Introduction

Ukraine's NPP sites have a well-developed network of underground pipelines of normal operation systems important for safety. A failure of those buried pipelines can lead to a failure of NPP safety systems and have a negative impact on the performance of safety functions. An essential service water system (hereinafter – ESWS) is an example of such a system. ESWS is a normal operation system important to safety with safety class 3 (NP 306.2.141-2008 "General Safety Provisions for Nuclear Power Plants"), group C (NP 306.2.227-202 "Safety Requirements on Design and Operation of Equipment and Piping of Nuclear Power Plants"), and the first category of seismic resistance (NP 306.2.208-2016 "Requirements for Seismic Design and Assessment of Seismic Safety of Nuclear Power Plants").

ESWS is designed for heat removal from the reactor core through the emergency cooling heat exchanger, heat removal from the spent fuel pool and other safety related equipment. The system's pipelines are laid underground at a depth of 2-6 meters.

ESWS is a part of the NPP Ageing Management Program. ESWS underground pipelines were covered in the ENSREG peer review in 2017 on the topic of "ageing management" [1]. Resulting from the peer-review, it was decided to develop a special program to manage the ageing of ESWS underground pipelines. Also, several theoretical aspects of solving the problem of underground pipe inspections were discussed in [2], [3], such as: improving the detection of defects in the early stages of their occurrence and improving the clarity of operational information about the object conditions.

Due to the inaccessibility of ESWS pipelines for external and internal inspection, it is necessary to use contactless diagnostics of ageing effects (metal thinning, corrosion changes, etc.) in relation to identified ageing mechanisms (cyclic fatigue, corrosion, etc.).

Acoustic methods that use a cross-correlation function (hereinafter – CCF) are widely deployed for diagnosis of underground pipelines. CCF signals from two space-separated sensors are an effective way to detect leakage of underground pipelines [4], flange connections in reactor shafts [5], and leaks of other vessels with gas or liquid under pressure.

Generally, useful information in the CCF carries its maximum that includes information on the degree and coordinate of the damage. However, in practice, this maximum is not always clear, distinct, and formed by important acoustic signals for analysis. This is due to the small signal-to-noise ratio, which is caused by both strong interference and an early, acoustically weak, stage of the diagnosed damage. Lack of accurate data on the frequency range of useful signals and the sensitivity of CCF to sensor locations are also complicating the CCF analysis. The complexity of decision-making in such conditions requires the development and application of a special parametric tool that simplifies and improves the analysis of CCF.

Analysis of the literature and statement of the problem

Improvement of correlation signal processing based on the use of the CCF spectrum in the analysis of pressure waves that occur during transients in the pipeline is discussed in [6]. The advantage of this method is an ability to use the reflected waves from obstacles in their path, in particular, from leaks. However, creation of such waves requires a sharp change in pressure in the pipeline. With regard to the analyzed area, this condition is technologically inconvenient and not always acceptable in terms of equipment wear, high safety requirements for the operation of pipelines at nuclear power plants, etc.

The method of selecting the signal sources by means of their frequency-time distributions is presented in [7]. The advantage of the method is the consistency of spatial and frequency selection of sources. However, this method is designed for non-stationary signals. It is not advisable to use transients in pipes, etc.

The method for determining the coordinates of the leaks, based on the use of generalized cross-correlation is outlined in [8]. It allows to take into account the multi wavelength and dispersion of the waves. However, this method requires significant hardware costs and complexity of data analysis causes difficulties in its application.

A coherence function is used when searching for leaks [9]. This function gives the operator information on which frequencies the correlation of signals is appeared in more or less extent. The information is used to adjust the frequency filters. However, this only reduces statistically unrelated barriers. Interference distortion caused by the registration of sensors of several coherent waves is not included. The coherence function does not give a clear frequency dependence of coordinates and other useful parameters, e.g., the signal-to-noise ratio considering statistically related interference, and does not take into account the impact on CCF sensor positions on the pipeline.

There is a method of applying the linear phase frequency spectrum of the CCF [10] which gives additional information about the frequency ranges needed to be considered by an operator. However, the method does not provide the required parametric picture.

There is a method of frequency-time analysis of correlation functions, which includes a 3-dimensional representation of narrow range components of CCF [11], [12]. Its advantage is the good completeness of the frequency and time content of the CCF. However, in relation to the problem to be solved, the method carries a lot of redundant information and does not take into account the impact on CCF positions of sensors on the pipeline.

Thus, it is important to develop a correlation parametric method for detecting and locating leaks which meets the requirements: the method should provide parametric and visual information to the operator about the dominant power of the signal source in frequency ranges with high resolution; the number of simultaneously analyzed frequency ranges should not be significantly limited by the way information is presented; the method should consider a sensitivity of the CCF to the locations of the sensors, in particular due to interference distortion; solve the problem of operational registration of damage in the early stages of occurrence with the definition of their coordinates.

Approbation results and experimental part

The accuracy of obtaining the initial data for the proposed method, estimates of the CCF, was ensured in accordance with methods [13], [14]. These references contain methods of coordinated selection of signal levels from sensors, the number of bits of analog-to-digital conversion, parameters of digital filters and algorithms for fast convolution in the development of correlation detectors. At the same time, the values of shifts and statistical errors of CCF estimates obtained through instrumental errors do not exceed the specified limits.

The approbation of the signal-to-noise ratio Q in relation to the CCF was performed in [15] in developing algorithms for automatic adjustment of the CCF filter, including the adaptive algorithm. It is shown in [15] that the maximization of Q in decomposing the original CCF on an orthogonal basis has an analytical solution: at the first stage the achievable maximum ratio for each CCF reading is determined and at the second stage is the graph of Q values.

The study of the impact on CCF spatial position of sensors on the pipeline was conducted in [16]-[18]. It was found that interference distortions of complex signals that occur during their registration can be taken into account by targeted and consistent parametric selection of signal recording points at the technological access points to the pipeline and frequency range, the appropriate method is proposed.

The first version of the parametric method was proposed in [19]. The method has passed many years of successful testing in Kyivenergo as a part of the diagnostic equipment for leak searching in the heating pipelines developed in the G. E. Pukhov Institute for Modelling in Energy Engineering of the National Academy of Sciences of Ukraine.

The basic assumptions of the method are discussed below. Firstly, the CCF is decomposed into narrow frequency range components using digital filters. Then, the parameters of the delay at which the maximum correlation is observed are determined for each frequency range considering the quality of the maximum correlation function (expressiveness, signal-to-noise ratio) and power. The results of the calculations are presenting in the form of three combined graphs as a function of the center frequency of the range filters. The plurality of waves, signal sources and space-frequency mechanism of their separation, as well as the final justification for the parameters of the CCF taking into account the spatial positions m of a pair of sensors on the pipeline, are justified in [20]. As a result, for a fixed position, *m* sensors received three spectra: power $A_m(f)$, signal-to-noise relationship $Q_m(f)$ and coordinates $L_{x_m}(f)$. There are $L_{xm}(f)$ frequency-resistant areas with almost the same coordinate values $L_{x_m}(f)$. Each such section is described by a set of coordinate values and the corresponding frequency range f = f1 ... f2, within which $L_{x_m}(f) \approx const$. This set of coordinates and the range of frequencies of its demonstration in the frequency-time structure of the CCF, which is convenient for correlation analysis, is conveniently called the coordinate flat part [18], [20] and is denoted as part of the coordinate spectrum $L_{x_m}(f)$ as $L_{x_{mf_1f_2}}$. Based on the flat parts, the probable coordinates of the damage could be justified and the appropriate values $A_m(f)$, $Q_m(f)$ and $f_2 - f_1$ determine the reliability of these coordinates. Therefore, these parameters, including $Q_m(f)$, are parameters of different quality of correlation and the corresponding coordinate flat part.

Interpretation of results and their approbation

An example of the application of the correlation parametric method for finding leaks in the heating pipelines comprise of a pair of sensors $m = 1$ and $m = 2$ is presented in Figure 1 and Table 1. Positions $m = 1$ and $m = 2$ differ from each other by the offset in the thermal chamber of one of the sensors along the axis of the pipeline by 2.4 m. Figure 1 (a) and (c) shows the obtained output CCF $R_m(T)$ at $m = 1$ and $m = 2$ respectively. In Figure 1 (b) and Figure 1 (d), the spectra of their parameters are presented in the normalized form. The actual leakage coordinate, determined after the pipeline was excavated, was 22.1 m from the fixed sensor. The values of the coordinate spectrum are calculated from the position of this sensor $L_{xm}(f)$ (see Table 1). Focus-resistant coordinates deserve the main attention $L_{Am\max}$ and $L_{Qm\max}$ with maximum values $A_{m\max}$ and $Q_{m\max}$ at the respective frequencies $f_{Am\max}$ and $f_{Qm\max}$. As it can be seen from Figure 1, the coordinates $L_{xAm\max}$ and $L_{xQm\max}$ are clearly demonstrated in the frequency range with relatively small fluctuations $L_{xm}(f)$ at the frequencies of the coordinate flat parts. In this example, they correspond to the frequency range with the main energy of the CCF, which is indicated by the graph $A_m(f)$. Outside this frequency range, chaotic behavior is observed $L_{x_m}(f)$ at relatively small values of the signal-to-noise ratio $Q_m(f)$. This is caused by statistical error of estimates. As follows from Table 1, the smallest error in determining the coordinate of the leak is accompanied by the highest quality parameters. It is the position $m = 2$ and the coordinate $L_{xQm\max} = 21.6$ m for $f_{Qm\max} = 1020$ Hz. In addition, the magnitudes of the differences are indicative $\Delta f_m = |f_{Am\max} - f_{Qm\max}|$ and $\Delta L_m = |L_{xAm\max} - L_{xQm\max}|$.

If the CCF of the leak is dominant, the smaller values give more accurate results of the leak search. Hence, Δf_m and ΔL_m are called discrepancies of power maximum and signal-to-noise ratio in frequency and coordinate. The discrepancies could be managed by shifting sensors to points of access to the pipeline, e.g., 0.5-3 m. It is observed that the value ΔL_m is often a good estimate of the resulting leakage coordinate error; therefore, ΔL_m is used as a criterion for the adequacy of measurements. Resulting from a such coordinated and frequency-spatial adjustment to the necessary type of waves of hydraulic shock, the smallest error of definition of coordinates of a leak is provided, see in Table 1 $\Delta L_{\Pi.m}$ at $m = 2$ compared to the value at $m = 1$.

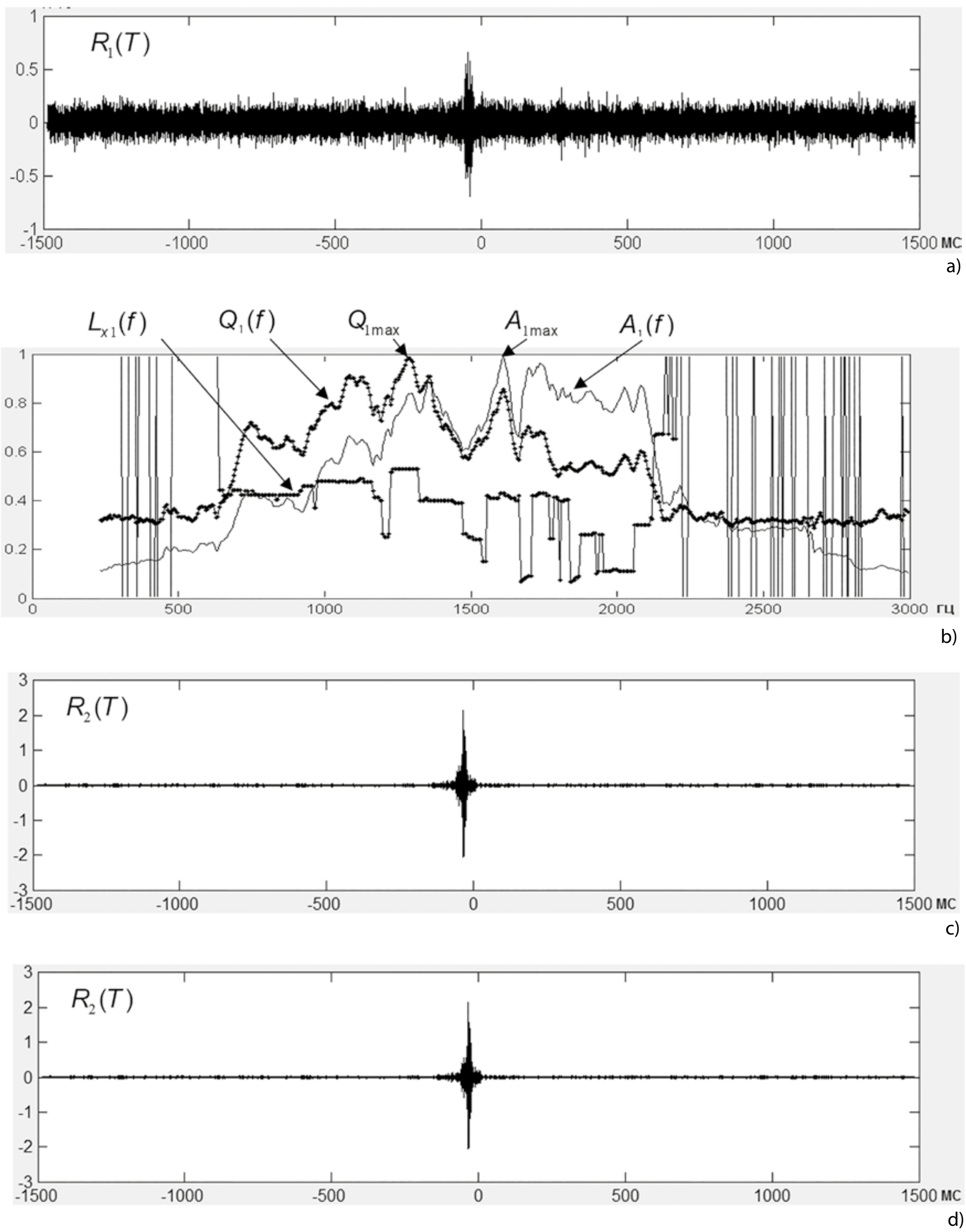


Figure 1 – Initial CCF of the sensors in position 1 (a), the normalized graph of its parameters (b), the graph of the original CCF of sensors in position 2 (c), the normalized graph of its parameters (d)

Table 1 – The results of the analysis of the CCF parameters

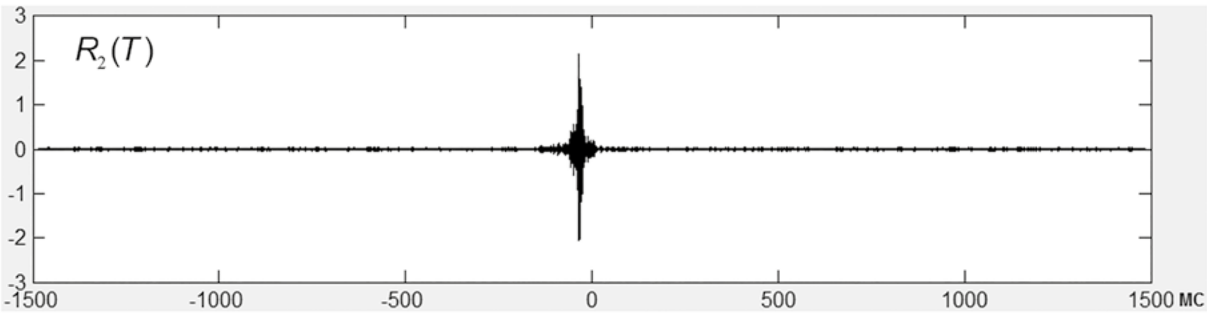
m	L_{xm} m	f_{Ammax} Hz	f_{Qmmax} Hz	L_{xAmmax} m	L_{xQmmax} m	Q_{mmax}	Δf_m Hz	ΔL_m m	$\Delta L_{П.m}$ m
1	18.3	1610	1285	18.9	20.8	12.1	325	1.9	1.3
2	21.0	820	1020	21.0	21.6	30	200	**0.6**	**0.5**

Coordinate flat rates are convenient to express indicator of the sensitivity of CCF assessment to presence (or absence) of informative correlation. It is of primary importance for the registration of the defect at an early stage, when it has been not developed into a large and clearly registered for CCF damage (see Figure 2). Figure 2a shows that the interval of the expressed informative correlation is not observed in the original CCF. This is due to the fact that the main energy of the CCF is indicated by the graph $A_m(f)$ in Figure 2b, so far formed by background noise, as evidenced by the highly oscillating type of the coordinate spectrum $L_{xm}(f)$ and low signal-to-barrier spectrum $Q_m(f)$. However, at low frequencies, in the range indicated Δf_K in Figure 2b, the damage that has already appeared is in the form of a coordinate flat part with relatively small oscillations in the coordinate $L_{xm}(f)$ and in the form of an increase in the spectrum $Q_m(f)$ signal-to-noise ratio.

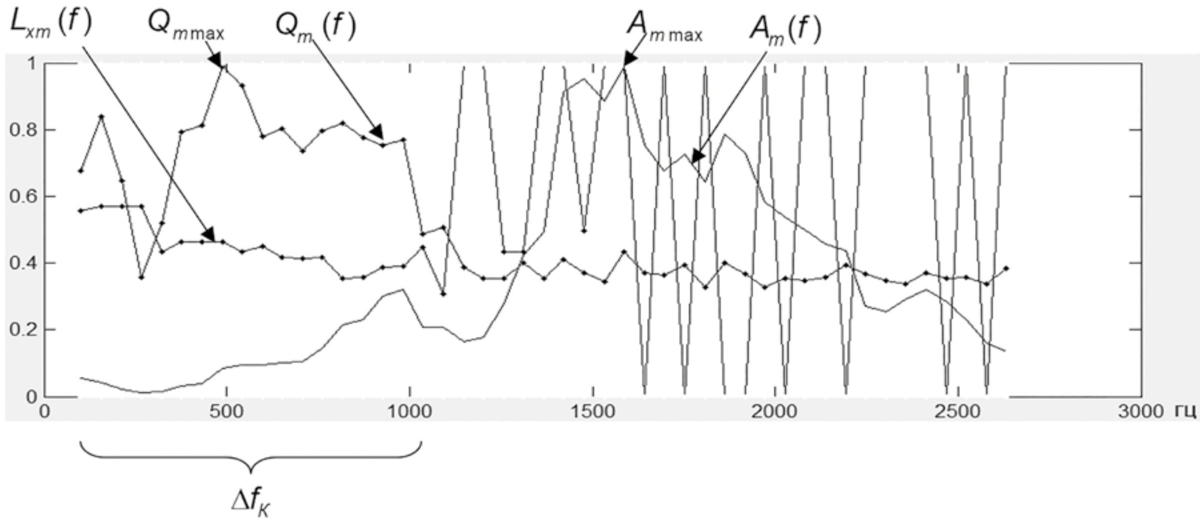
This method in parametric and visual form provides the operator with the necessary information about the dominant power of the signal source. The number of simultaneously analyzed parameters of the CCF frequency ranges is almost unlimited. Coordinated choice of frequency range and position of sensors on the pipeline provides reliable selection of the most informative and powerful waves with a known group speed, in particular hydraulic shock waves, in terms of their interference distortions. Parametric structures in the form of coordinate flat rates and the corresponding spatial-frequency parameters of the CCF allow to quickly register damages in the early stages of their appearance.

Conclusion

The developed parametric method is an efficient tool to simplify and improve the analysis of CCF that is confirmed by the practical experience of its application in urban heating pipelines. Joint use of contactless acoustic and magnetometric diagnostics can increase the probability of detecting areas of various types of defects in the metal of the pipeline, which is crucial to determining the technical conditions of underground pipelines inaccessible to contact non-destructive contact methods [21].



a)



b)

Figure 2 – The case of lack of visible useful correlation in the original CCF. The graph of the original CCF (a) and the normalized graph of the spectra of its parameters (b) with the leak in the frequency range Δf_K

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Taking into account the specifics of NPP process systems with underground (concealed) pipelines, such as ESWS, and their importance to NPP safety, the following aspects need to be considered:

1. The basic correlation method of finding leaks is based on the registration of acoustic noise emitted by the leakage from the damaged pipe. The acoustic noise could be generated in case of sufficiently high excess pressure in the pipeline. The minimum pressure level required by typical conventional correlation leak detectors is 1.5-2 kgf/cm^2. The pressure in the ESWS underground pipelines is in the range of 0.6-5.5 kgf/cm^2 [22]. Hence, the proposed method can be used to inspect parts of the NPP underground pipelines with operating pressure higher than 2 kgf/cm^2. Some exceptions could be given for areas with a pressure close to 2 kgf/cm^2 with a pipe length of about 200 m or more.

2. Regarding diagnostics for sections of NPP pipelines with a pressure of less than 2 kgf/cm^2, as well as in the above exceptional cases, higher sensitivity is required compared to the basic correlation method. As demonstrated in Figure 2, the proposed parametric method could ensure the needed senility but additional testing needs to be done for low-pressure NPP pipelines. The tests should be carried out considering the actual design characteristics and conditions of underground low-pressure NPP pipelines. Sensitivity of the correlation parametric method in decreasing operating pressure in the pipeline should be further studied.

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Параметричний аналіз кореляційних функцій у задачах акустичного контролю і діагностики підземних трубопроводів АЕС

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Моніторинг та оцінка технічного стану підземних трубопроводів технологічних систем, важливих для безпеки, є актуальним завданням процесу управління старінням діючих АЕС. Для вирішення цього завдання можуть бути застосовані методи, апробовані в інших галузях промисловості, де в експлуатації знаходяться заглиблені в землю нафтопроводи, газопроводи, трубопроводи комунально-побутових служб тощо. Стаття присвячена теоретичним питанням подолання перешкоджаючої надмірності, що міститься у взаємних кореляційних функціях, акустичного методу дослідження підземних трубопроводів.

Наведений параметричний метод аналізу заснований на суміщеному за частотою відображенні спектрів потужності, відношення сигнал-перешкода і координати для кожного домінуючого в окремій смузі частот сплеску взаємної кореляційної функції. Наочність і частотна повнота уявлення лише необхідних властивостей кореляційної функції полегшує їх просторовий аналіз. Такий аналіз часто є необхідним через високу чутливість кореляційних функцій до вибору місць реєстрації сигналів. Показано ефективність методу під час пошуку витоків у підземних трубопроводах в умовах інтерференційних спотворень та малого відношення сигнал-перешкода. Спектр відносин сигнал-перешкода вирішує завдання функції когерентності, проте з урахуванням корельованих перешкод та у зручній прив'язці до координати. Показано корисний практичний прояв та застосування параметричної структури у вигляді плоских частин у спектрі координати-координатних поличок та параметрів неузгодженості спектрів потужності та відношення сигнал-перешкода під час пошуку витоків.

Метод пройшов апробацію під час інтенсивного пошуку витоків у міських теплових мережах і може бути корисним для виявлення витоків на ранніх стадіях їх появи в підземних трубопроводах систем технічної води відповідальних споживачів АЕС.

Ключові слова: інтерференція, координата, кореляція, параметричний, течешукання, трубопровід.

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