The object of this study is the dynamics of hazardous parameters of the gas environment when materials are ignited in the premises. The task addressed was the early detection of fires in the premises. It is proposed to resolve this issue on the basis of using an assessment of the coherence of frequency components in the third-order spectrum relative to the dynamics of hazardous parameters of the gas environment. The results indicate the nonlinear nature of the dynamics of hazardous parameters of the gas environment both in the absence and in the presence of fires. It was established that the assessment of the coherence of the frequency components relative to the considered triplets in the third-order spectrum contains information on the ratio of order to chaos in the dynamics of hazardous parameters of the gas environment. This information can be used to reliably detect fires. It was found that when the test materials in the form of alcohol, paper, wood, and textiles are ignited, the ratio of order to chaos in the temperature and CO dynamics in a gaseous medium is halved. It was established that the average values for frequency indices from 0 to 20 of the coherence of the frequency components of the dynamics of hazardous parameters on the ignition interval of test materials are in the range from +0.005 to –0.187. At the same time, in the interval of absence of ignition of test materials, the average values of the coherence assessment for frequency indices from 0 to 20 are in the range from +0.48 to +0.022. The reported results generally indicate the prospects and further development of studies into the coherence of the frequency components of the third-order spectrum for the dynamics of hazardous parameters of the gas environment in order to detect fires in the premises

Keywords: coherence, third-order spectrum, parameter dynamics, gas medium, room, ignition

UDC 621.03.9
DOI: 10.15587/1729-4061.2022.268437

REVEALING THE FEATURES OF THE THIRD ORDER PHASE SPECTRUM OF THE MAIN DANGEROUS PARAMETERS OF THE GAS MEDIUM

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Received date 09.09.2022
Accepted date 30.11.2022
Published date 29.12.2022

***How to Cite:** Pospelov, B., Bezuhla, Y., Yashchenko, O., Khalmuradov, B., Petukhova, O., Gornostal, S., Kozar, Y., Tishechkina, K., Salamatina, O., Ihnatenko, Z. (2022). Revealing the features of the third order phase spectrum of the main dangerous parameters of the gas medium. Eastern-European Journal of Enterprise Technologies, 6 (10 (120)), 63–70. doi: https://doi.org/10.15587/1729-4061.2022.268437*

1. Introduction

An important and common problem of our times is to ensure the safety of the functioning of various facilities [1]. A special place is given to critical infrastructure facilities [2, 3]. This is due to the fact that such objects are sources of various types of dangerous events at them [4]. Dangerous events are also characteristic of most objects of the technical and environmental sphere [5, 6]. In addition, they can also occur in various objects of the socio-economic sphere [7, 8]. However, hazardous events at facilities are characterized by different levels of damage and frequency of their occurrence. From the point of view of the damage caused, as well as the frequency of occurrence, there are dangerous events in the form of a fire in the premises (FP) of objects in both the technical and residential spheres [9]. This is explained by that FP cause significant damage to both a person [10, 11] and objects [12]. In addition, the consequence of FP is damage to the environment [13, 14]. At the same time, according to world statistics, the measures and technical means used to protect against FP are not sufficiently effective. Therefore, an important direction in ensuring the safety of the functioning of various facilities, first of all, should be considered protection against FP. Since the source of any fire is ignition (I) turning into fires, protection against FP is reduced to preventing the transition of I into fires. In this regard, the detection of fires (DI) should be considered a particularly urgent problem.

2. Literature review and problem statement

Paper [15] notes that early DI should be considered a constructive approach to reducing damage from FP. In [16] it is proposed to analyze various hazardous parameters of the gaseous environment (GE) of the premises for DI. At the same time, the analysis of hazardous GE parameters in [16] is limited to the time domain. The frequency domain is not used for analysis. [17] shows that hazardous GE parameters are non-stationary. In [17], the non-stationary characteristics of the hazard parameters of GE in I are investigated. To increase the efficiency of the analysis of non-stationary GE parameters, a high-speed method of analysis is proposed and investigated in [18]. However, the method is limited to considering the schematic approach in the time domain. At the same time, the frequency domain of analysis is not considered, and the circuit approach is limited to considering only the temperature parameter of GE. In [19], for DI under non-stationary conditions of GE parameters, adaptive approaches are considered. However, in [19], adaptive technologies are limited only to non-stationary energy characteristics of hazardous GE parameters in the time domain. The use of group processing of data from a set of sensors of hazardous GE parameters and network technologies for DI is considered in work [20]. The development of technology for group processing of data from two or more sensors of various hazardous parameters of GE of premises for the purpose of reliable DI is considered in [21]. Some of these technologies are implemented in EN and ISO standards [22–24]. [22] describes the DI technology based on a combination of CO sensors and GE temperature. However, the expansion of the capabilities of the technology [22] is not envisaged. [23] discusses the technology of using multiple sensors to detect FP with the function of monitoring the status of sensors. However, this technology does not allow indoor DI. It, like the technology in [22], is limited to measuring GE parameters only in the time domain. ISO [24] discusses the technology of using the CO sensor in conjunction with one or more thermal sensors to detect FP. However, this technology does not apply to the use of CO and heat sensors with special characteristics that allow DI. It is proposed to use different types of smoke detectors to detect FP [25]. Smoke detectors have high speed and relatively low cost. However, such sensors have a high probability of false DI, which is significantly dependent on the ambient temperature [26]. For this reason, combined smoke [27] and temperature sensors [28] are used for reliable DI. Therefore, new types of FP detection sensors combine several sensors of various hazardous parameters [29]. Due to the importance for DI, the pyrolysis processes of various combustible materials (CM) and the corresponding dynamics of hazardous GE parameters, [30] studies the characteristics of the hazardous parameters of GE in plantation wood. The study of the influence of the rate of heat release from the intensity of wood burning is reported in [31]. However, in [31], studies are limited to only the average rate of heat generation and the average intensity of combustion. The rate of heat generation from the intensity of combustion of organic glass and cypress is investigated in [32]. At the same time, in [30–32] there are no results of a study of the characteristics of the spectra of the second and third order of hazardous parameters of GE. Due to the diversity and objective complexity of the real dynamics of the hazardous parameters of GE of the premises at I, new approaches to the analysis of the features of the real dynamics of the hazardous parameters of GE are required. Therefore, approaches to DI based on the analysis of fractal characteristics of the dynamics of hazardous parameters of GE of premises are becoming relevant [33–36]. Work [33] considers an approach based on the analysis of the correlation dimension of the dynamics of the vector of the state of hazardous parameters of GE. An approach based on the method of recurrent diagrams for the dynamics of CO concentrations for the purpose of indoor DI is considered in [34]. Prediction of W based on the measure of recurrent state vector GE is considered in [35]. Work [36] considers the modification of Brown's forecasting model. And [37] considers the adaptive method of calculating the recurrent diagram of hazardous parameters of GE [37]. However, these approaches are limited to considering the dynamics of hazardous parameters of GE in the time domain. New approaches considered in [33–37] do not use the spectral region. The development of a correlation method for the rapid detection of recurrent states is considered in [38]. The use of a structural method for identifying hazardous states of GE is considered in work [39]. The use of the uncertainty function to identify hazardous GE conditions is discussed in [40]. However, studies [38–40] are limited to the dynamics of hazardous parameters without taking into account spectral characteristics. In [41], the instantaneous amplitude and phase spectra of the dynamics of hazardous parameters of GE of the premises in the frequency domain are investigated. At the same time, it is noted that the amplitude frequency spectra are uninformative for DI. Such a conclusion in [41] is made on the basis of the analysis of amplitude frequency spectra of only the second order, which does not make it possible to identify the spectral correlation of frequency components due to the nonlinearity of the dynamics of the dangerous parameters of GE of the premises. The spectra of dynamics of hazardous GE parameters of the order higher than the second, capable of detecting the nonlinearity of dynamics, are not analyzed. In [42], it is noted that the ceiling zone is the most suitable for DI in the premises. Therefore, most known models describe the dynamics of hazardous GE parameters in the ceiling zone [43] and are deterministic. [44] considers a general mathematical model of the quality of detection of fire detectors. However, in works [43, 44], the models are limited to the time domain.

At the same time, [43] notes that most models need to be checked by fire tests. The results of fire tests, taking into account the effects of various interfering factors of GE, are considered in [45]. According to the results of fire tests, it is noted that for a reliable DI it is necessary to take into account together the dynamics of CO concentration and smoke density. Paper [46] reports the results of an experimental study of the mutual relationship between various hazardous parameters of GE at I. However, the reciprocal relationship of parameters is limited to the evaluation of mutual correlation, which takes into account only the linear relationship. Spectral characteristics of the order above the second, which make it possible to identify nonlinear relationships of parameters for DI, are not considered and investigated. The third-order amplitude spectra of hazardous GE parameters in the laboratory chamber are considered in [47]. It is shown that the amplitude spectra of the third order make it possible to identify nonlinear relationships of frequency components in the spectrum of GE parameters, but the degree of their detection significantly depends on the magnitude of a particular hazardous parameter. The coherence of the frequency components of the third-order spectra, which does not depend on the magnitude of the dangerous parameter, is not considered. Thus, the features of the coherence of frequency components in the spectrum of the third order for hazardous GE parameters at I in the premises are not investigated. Therefore, an important and unsolved part of the problem of DI should be considered the analysis of the coherence of the frequency components of the spectrum of the third order for the dynamics of the main hazardous parameters of GE at the stage of I occurrence of various materials in the premises.

3. The aim and objectives of the study

The purpose of this work is to determine the features of the phase spectrum of the third order of the main hazardous parameters of the gas environment for the intervals of absence and occurrence of fire in the premises. The results of the study will allow them to be used in the future for the early detection of fires in the premises.

To accomplish the aim, the following tasks have been set:

– to perform a theoretical substantiation of the study of the coherence of frequency components in the spectrum of the third order for an arbitrary dangerous parameter of the gaseous medium during the ignition of materials;

– to identify the features of the coherence of the frequency components of the spectrum of the third order for hazardous parameters of the gas medium at intervals of absence and presence of ignition of test materials.

4. The study materials and methods

The object of this study is the coherence of the frequency components in the spectrum of the third order of hazardous GE parameters in the absence and presence of I CM in the room. The main working hypothesis is the difference in the coherence of frequency components in the spectrum of the third order for hazardous GE parameters at intervals of absence and presence of I. The identification of such differences will allow them to be used to detect I and prevent FP. Accepted assumptions and simplifications consist in the assumption that the dynamics of hazardous parameters of GE in I CM in real premises is similar to the dynamics of hazardous parameters of GE in a laboratory chamber [44] at I of the same CM. In a chamber [44], it is possible to simulate the dynamics of hazardous GE parameters in the ceiling area of leaky rooms at different CM. In the experiment, alcohol, paper, wood, and textiles were used as CM. The gas parameters of GE in the chamber were temperature, smoke density, and CO concentration. Temperature measurement was carried out by the TPT-4 sensor (Ukraine), the smoke density by the DIP-3.2 sensor (Ukraine), and the concentration of CO by the Discovery sensor (Switzerland). The results of measurements from the outputs of the corresponding sensors were stored in the computer memory with an interval of 0.1 s. Forced I CM in the chamber was made at the time of t_{200}. This condition guaranteed the absence of I up to this point in time. Therefore, the features of the coherence function of the frequency components in the third-order spectrum for the dynamics of the measured hazardous GE parameters in the chamber were studied for two time intervals of equal duration equal to 100 samples. At the same time, the first interval is limited to the 100th and 200th measurements and corresponds to the reliable absence of I. The second interval is limited to the 200th and 300th measurements and includes the moment of the beginning of the forced I CM in the chamber. Features of the coherence function at these intervals were studied for each CM in the following order: alcohol, paper, wood, and textiles. To restore the hazardous parameters of GE in the chamber after the I of each CM, its natural ventilation was carried out within 5 minutes.

5. Results of the study of the features of the phase spectrum of the third order of the parameters of the gas medium

5. 1. Theoretical substantiation of coherence research for an arbitrary hazardous parameter of the gaseous medium

Higher-order spectra are a toolkit for the reliable detection and identification of higher harmonics in the processes under study [48]. The use of third-order spectra to detect the I of electrical equipment is considered in [49]. At the same time, in [50] it is noted that high-order spectra are a powerful toolkit to identify features of non-Gaussian processes and suppress additive Gaussian interference. In addition, such spectra contain more information than traditional second-order spectra. A third-order spectrum is often called a bispectrum. Estimation of bispectrum $B(h1, h2; T)$ for a fixed time interval T and the discrete set $\{x(k)\}$ of the values of the process under study given on it, following [51], will be determined as:

$$B(h1,h2;T)=X(h1;T)X(h2;T)X^*(h1+h2;T), \qquad (1)$$

where $B(h1, h2; T)$ is a function of variables $h1$, $h2$ for the interval T, meaning the corresponding frequency indices;

$$X(h;T)=\sum_{k=0}^{N-1}x(k)\exp(-j2\pi hk/N),$$

$(0\le k\le N-1)$ defines the Fourier transform for the frequency index h $(0\le h\le N-1)$ and the discrete set $\{x(k)\}$ of the values of the process under study at a given interval; * – the operator of complex conjugation. At the same time, an arbitrary frequency index h corresponds to the frequency $f=h/T$. Here, the value T defines the time interval in seconds for the discrete set $\{x(k)\}$. The bispectrum estimate defined by (1) is a composite value, which means that the estimate (1) is determined by the corresponding actual Re[$B(h1,h2;T)$] and imaginary Im[$B(h1,h\ 2;T)$] in parts. The actual part of the evaluation (1) characterizes the time-reversible component for a given discrete set {$x(k)$}. The imaginary part carries information about irreversible changes in the discrete set {$x(k)$}. Therefore, the estimation of coherence $\varphi(h1,h\ 2;T)$ of the frequency components (1) on the interval of duration T can be determined:

$$\varphi(h1,h2;T)= \\ =\mathrm{arctg}\left\{\mathrm{Im}\left[B(h1,h2;T)\right]/\mathrm{Re}\left[B(h1,h2;T)\right]\right\}. \quad (2)$$

For the convenience of further investigation, it is proposed to determine the coherence assessment (2) in accordance with the expression:

$$Cbis2(h1,h2;T)=\cos\left[\varphi(h1,h2;T)\right]. \quad (3)$$

Following expression (3), the coherence assessment $Cbis2(h1,h2;T)$ at interval T satisfies the inequality $-1\leq Cbis2(h1,h2;T)\leq 1$. This means that the values of the estimate equal to 1 correspond to the complete coherence of the frequency components of bispectrum $B(h1,h2;T)$, and the estimate values of –1 correspond to their complete opposite coherence. An estimate value of zero corresponds to the absence of complete coherence between the frequency components in spectrum (1). The intermediate values of estimate (3) will correspond to different levels of coherence of the frequency components in the specified spectrum. In other words, the intermediate values of estimate (3) numerically determine the relationship between the reversible (order) and the irreversible part of the bispectrum, which reflect the ratio of order and chaos in the study set {$x(k)$}. The accuracy of estimate (3) depends on the accuracy of the estimation of the spectrum $X(h;T)$, which is inversely proportional to the duration of the T analysis interval. Following [52], with an increase in the duration of T, the accuracy of estimating the spectrum $X(h;T)$ increases. Studies [53, 54] show that, in general, for large intervals of T (N values), estimates of the real and imaginary parts of bispectrum (1) are asymptotically unbiased and solvent. The estimation of coherence (3), in contrast to the estimate of amplitude bispectrum, does not depend on the values of the process under study and makes it possible to study the coherence of bispectrum for arbitrary triplets determined by arbitrary frequency indices $h1$, $h2$ and $h1+h2$, respectively. Therefore, the objective of the considered study is to assess coherence (3) of the bispectrum for hazardous GE parameters at intervals of absence and presence of typical CM I.

5. 2. Features of coherence of gas parameters in the absence and presence of fires of materials

The study of coherence features (3) was performed for intervals of equal duration of T of the reliable absence and presence of I of tested CM in a chamber. The estimate (3) was determined for the special case of the frequency triplet $h1$, $h1$ and $h1+h1$. The advantage of this type of triplet is that it is determined by the value of only one frequency index $h1$. This makes it possible to investigate particular features of coherence estimation for frequency components determined by frequency indices $h1$ and $2h1$ in the frequency spectrum of dynamics of hazardous GE parameters. Fig. 1 shows the results of the coherence assessment (3) for the specified type of triplet at different values of the frequency index $h1$ at the intervals of absence and presence of I.

The results of the assessment for the dynamics of GE temperature at the intervals of absence and presence of CM I are shown in Fig. 1, *a*, *b*. Similar results for the smoke and CO dynamics are depicted in Fig. 1, *c*, *d*, and Fig. 1, *e*, *f*, respectively.

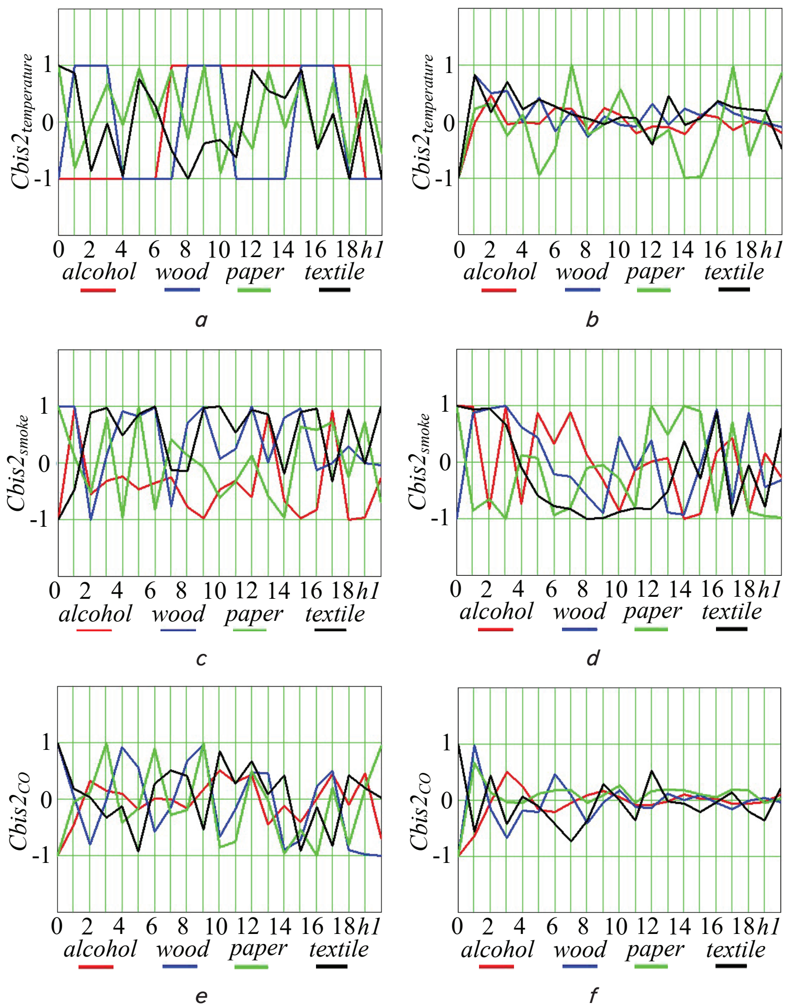

Fig. 1. Results of the coherence assessment for the dynamics of temperature, smoke, and CO in the case of a given type of triplet at different values of the frequency index $h1$ at different intervals: *a*, *c*, *e* – no fires; *b*, *d*, *f* – presence of fires

6. Discussion of results of the study of the features of the phase spectrum of the third order of the parameters of the medium

From the analysis of the results in Fig. 1, it follows that the dynamics of temperature, smoke density, and CO concentration for GE in the chamber at the intervals of absence and presence of I of alcohol, paper, wood, and textiles are Non-gaussian. The non-gaussian character is explained by the presence of different coherence for frequency components in the dynamics spectrum of the studied hazardous parameters. For example, coherence in the spectrum of temperature dynamics GE (Fig. 1, *a* – red curve) at the interval absence of I is observed for a greater number of frequency components. At the same time, for the frequency components corresponding to the indices *h*1, equal to 0–6, 19, and 20, the coherence is opposite (the phase difference is 180°). The presence of coherence and opposite coherence indicates the predominance in the temperature dynamics of order over chaos in the interval of absence of I. For the dynamics of smoke density and CO concentration, the degree of coherence in the interval of absence of I is irregular in the range from +1 to –1 (Fig. 1, *c*, *d* – red curve). At the same time, the number of frequency components with high coherence is significantly less compared to temperature. This means that in the dynamics of smoke density and CO concentration for GE, the ratio of order to chaos, decreases. The irregular nature of the coherence assessment for the frequency components of the dynamics of smoke density and CO concentration in the absence of paper, wood, and textiles (Fig. 1, *a*, *c*, *e*) is explained by the peculiarities of the experimental conditions. The assessment of the coherence of the frequency components of the dynamics of hazardous parameters of GE in the chamber at the interval of absence of I was carried out after the I of alcohol, paper, and wood with natural ventilation of the chamber for a limited time. Apparently, the natural ventilation of the chamber after the I of the corresponding CM was insufficient to fully restore the original dynamics of the hazardous parameters. The results of the coherence assessment at interval I of the tested CM in Fig. 1, *b*, *g*, *e* indicate a violation of the initial relationship between order and chaos in the dynamics of the studied dangerous parameters of GE. This is most characteristic of temperature dynamics (Fig. 1, *b*) and CO concentration dynamics (Fig. 1, *e*). Violation of the initial relationship between order and chaos in the dynamics of these dangerous parameters of GE is manifested in a decrease in this ratio by almost half. This is due to the predominance of chaos over order in the corresponding dynamics of these dangerous parameters for all tested CM. For an approximate numerical expression of the ratio of order and chaos in the dynamics of hazardous GE parameters, you can use, for example, the average value or other statistical characteristics of estimate (3) for a given range of frequency components. In this study, the given frequency range was determined by the values of the frequency index from 0 to 20. It should be borne in mind that the value of estimate (3), equal to ±1, corresponds to coherence or order, and zero or close to zero its values correspond to chaos. Therefore, the intermediate values of estimate (3) lying in the range from 0 to ±1 will numerically characterize the order-to-chaos ratio for the corresponding frequency index. For example, the values for assessing the coherence of the frequency components of the dynamics of hazardous parameters at the interval of CM I for the frequency index range from 0 to 20 lie in the range from +0.005 (smoke density – paper) to –0.187 (smoke density – textiles). At the interval of absence of CM I, the average values of the coherence assessment for this range of frequency indices are in the range from +0.48 (smoke density – textiles) to +0.022 (smoke density – wood). Thus, the results generally indicate the non-Gaussian nature of the dynamics of the studied hazardous GE parameters in the chamber, both at absence intervals and at intervals I of the test CM. At the same time, the assessment of coherence (3) of the frequency components indirectly characterizes the ratio of order to chaos in the dynamics of the studied dangerous parameters of GE. This makes it possible to use the estimate value (3) for certain frequency components of the dynamics of hazardous GE parameters at given intervals as a working sign of detecting CM I at these intervals. The temporal localization of the detection of I is determined by the localization in time of a given interval. However, the accuracy of assessment (3) depends mainly on the duration of this interval and the sampling rate of the measurements. The longer the duration of the specified interval, the more precise the calculation of the spectrum and, accordingly, the coherence of the frequency components of the measured GE parameter, but the temporal localization deteriorates. In the study, the estimation of the coherence of the frequency components was determined by 100 discrete measurements of the hazard parameter with a sampling frequency of 10 Hz. In this case, the duration of the specified interval was 10 seconds. For this interval, the frequency resolution was 0.1 Hz. For this case, the temporal localization of I was limited to an interval of 10 seconds. This localization accuracy is sufficient to detect I.

In general, the results obtained indicate the solution of an important and unsolved part of the problem of DI since they reveal the coherence of the frequency components of the third-order spectrum for the dynamics of the main hazardous parameters of GE at the stage of I occurrence of materials in the premises. At the same time, the advantage of this seminal study lies in the novelty of the proposed assessment of the coherence of the frequency components, as well as the originality of the results obtained for a given triplet in the spectrum of dynamics of hazardous GE parameters. At the same time, such estimates allow them to be used for early detection of I. Limitations include the fact that the coherence assessment study was performed on the basis of experimental measurements of hazardous GE parameters in a laboratory chamber. However, the results obtained generally indicate the prospects for studying the coherence of the frequency components of the third-order spectrum for the dynamics of hazardous GE parameters in order to detect I in the premises.

7. Conclusions

1. A theoretical substantiation of the study of the coherence of frequency components in the spectrum of the third order for an arbitrary dangerous parameter of the gas medium at a given interval is carried out. The basic one is to determine the complex spectrum of the third order for the dynamics of the dangerous parameter of the gas medium at a given time interval and the subsequent calculation of its argument. At the same time, it is proposed to assess coherence on the basis of the cosine argument for a third-order complex spectrum. This makes it possible to investigate the coherence of frequency components for an arbitrary dangerous parameter of the gas medium at a given interval.

2. The features of the coherence of the frequency components of the spectrum of the third order for hazardous parameters of the gas medium at intervals of absence and presence of ignition on the example of ignition of test materials in the laboratory chamber are revealed. The results obtained indicate the non-Gaussian nature of the studied hazardous parameters of the environment both at the interval of absence

and at the interval of appearance of ignition of materials. It is established that the coherence of the frequency components of the complex spectrum of the third order contains information sufficient to detect violations during the ignition of materials. It is obtained that during the ignition of materials, the coherence of the frequency components of the third-order spectrum for a dangerous parameter of the gaseous medium and the transition to its chaotic change decreases. It was found that the studied assessment of coherence for temperature and CO in GE is reduced by almost half. At the same time, the average values of the coherence assessment for frequency indices from 0 to 20 for hazardous parameters of the gas environment at the interval of the beginning of ignition of test materials lie in the range from +0.005 to –0.187. At the interval of absence of material ignition, the average values of the coherence assessment are in the range from +0.48 to +0.022.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was conducted without financial support.

Data availability

The manuscript has associated data in the data repository.

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