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COMPARISON OF BICOHERENCE ON THE ENSEMBLE OF REALIZATIONS AND A SELECTIVE EVALUATION OF THE BISPECTRUM OF THE DYNAMICS OF DANGEROUS PARAMETERS OF THE GAS MEDIUM DURING FIRE

The object of the study is the bicoherence of the bispectrum assessment of the dynamics of dangerous parameters of the gas environment during the ignition of materials. The subject is a measure of bicoherence of the bispectrum estimation from the ensemble of realizations and selective bispectrum estimation for the dynamics of hazardous parameters of the gas environment. The practical importance of the research is the use of the measure of bicoherence of the bispectrum for the early detection of fires. The measure of bicoherence of the dynamics of hazardous parameters of the gas environment is substantiated, which allows them to be numerically compared for the studied bispectrum estimates. As such measure, it is proposed to use the integral value of bicoherence for a given frequency interval, which makes it possible to numerically compare the bicoherence of bispectrum estimates for arbitrary time intervals of the dynamics of hazardous parameters of the gas environment. On the basis of the proposed measure for the frequency range of 0.2–2 Hz, a comparison of the integral bicoherence of the bispectrum estimates was made. The numerical value of the measure was determined for three fixed time intervals of the dynamics of hazardous parameters of the environment, corresponding to the absence of ignition, the occurrence of ignition, and the subsequent burning of test materials in the laboratory chamber. According to the results of the comparison of such values, it was established that the bicoherence of the bispectrum estimation from the ensemble of realizations is the most appropriate for detecting fires. When ignited, the numerical value of the measure for all test materials is about 90°. This means that the nature of the dynamics of hazardous environmental parameters in the event of fires becomes random. In this regard, the proposed measure is recommended to be used as a test for early detection of fires

Keywords: early fire detection, bispectrum assessment, bicoherence, dangerous parameters, gaseous medium

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1. Introduction

Ensuring the resistance of facilities to man-made [1] and natural threats [2] is one of the most important problems for any state. A special place is occupied by the problem of ensuring the sustainability of critical infrastructure facilities [3, 4]. This is due to the fact that such facilities themselves are sources of threats and emergencies [5], and their activities are key to the state's economy and the livelihoods of the population [6]. In addition, most of the objects of the technical, environmental sectors [7] and a number of objects of the socio-economic sector are also potential sources of danger [8]. The most intense are dangerous events related to fires [9]. Fires lead to death and injury to people [10], destruction and damage to industrial [11] and housing facilities [12, 13]. Combustion products, extinguishing agents, as well as by-products of fire equipment [14] cause pollution of water sources [15], soils, and atmospheric air [16]. The maximum frequency of occurrence and the greatest damage are characteristic of indoor fires (IF) [17]. However, despite the use of advanced technologies to combat IF [18], their frequency and damage continue to increase [19]. In this regard, the fight against IF should be considered as an important direction for ensuring the sustainability of various facilities [20]. Fire fighting is based on two areas. Prevention involves preventive measures [21], early detection and prediction of fires [22]. Extinguishing implies timely response with a sufficient amount of resources. If the fire is not detected at an early stage, this leads to its more intensive development, increases the extinguishing time, and consequently the damage caused. Given that the source of IF is the ignition of materials (IM), the problem of combating IF is reduced to the timely detection of IM and the prevention of fires [23]. Therefore, early detection of fires (DF) is relevant.

2. Literature review and problem statement

The difficulty of solving the problem of early DF is the non-stationarity and nonlinearity of the real dynamics of hazardous parameters (DHP) of the gaseous medium (GM) at *Z*. Therefore, known studies are aimed at finding ways of early DF under conditions of non-stationarity and nonlinearity of real DHP. In [24], adaptive technologies of early DF under conditions of non-stationarity of DHP of GM at premises are investigated. At the same time, studies are limited only to the time domain and Gaussian static non-stationarity. This means that these technologies are not applicable in a non-linear case. The frequency domain and use of statistics above the second order of GM DHP are not investigated. Paper [25] examines the technology of group processing of data from multiple sensors and the network principle for early DF under conditions of non-stationarity and nonlinear nature of GM DHP at IM. A multi-sensory building fire alarm system with information integration technology based on D-S theory is considered in [26]. It is noted that this technology is complex and has limited capabilities of early DF under non-stationary conditions and with the non-linear nature of GM DHP. This is explained by the temporary GM DHP and statistics that are not sensitive to the peculiarities of its non-linear nature. The study of the experimental dynamics of GM temperature at IM of wood is reported in [27]. The dependence of the experimental dynamics of GM temperature on the intensity of the external heat source on the nature of wood combustion is investigated in [28]. However, the studies are limited to the average temperature dynamics and the intensity of the external heat source, which do not take into account nonlinear effects. Similar studies for organic glass and cypress are performed in [29]. However, in [27–29], there are no studies of the temporal and spectral characteristics of GM DHP, which make it possible to identify the features of its nonlinear nature. In [30], a technology is investigated that is able to identify non-specific features of GM DHP based on the determination of its correlation dimensionality. However, this technology is applicable only to one arbitrary hazard parameter of GM and does not make it possible to identify non-linear features for an arbitrary vector of GM DHP determined by the set of hazardous GM parameters. The technology of identifying nonlinear features of an arbitrary vector of GM DHP based on the use of recurrence plots is considered in [31]. However, the technologies in [30, 31] are parametric. Therefore, the ability of these technologies to detect early DF depends significantly on the compliance of the parameter value with the current energy ratio of the dangerous factor of ignition and the background factor. In this case, the energy of the dangerous factor should exceed the energy of the background factor by more than twice. Under conditions of uncertainty of the energy ratio of the dangerous factor of ignition and the background factor, the technology of adaptive recurrent plots is proposed in [32]. However, the above technologies, despite the ability to identify the features of nonlinear GM DHP, are limited to the time domain. At the same time, the background factor limiting the potential of technologies is characterized in most cases by Gaussian statistics. Technologies for using the frequency domain to identify nonlinear features of GM DHP, taking into account the Gaussian nature of background factors, are not considered. As part of the application of the traditional approach, the technologies of correlation analysis of GM DHP [33], the structural function [34], and the uncertainty function [35] are investigated. However, the study of these technologies is limited to the time domain. The frequency domain is not considered and the correlation of spectral components characteristic of the nonlinear features of the GM DHP is not investigated. In [36], the mutual relationships of various hazardous parameters of GM are investigated. However, these studies are limited to the evaluation of only correlational relationships, which make it possible to identify the degree of exclusively linear relationship. At the same time, statistics of the order higher than the second, capable of identifying nonlinear relationships, are not investigated. In [37], the features of the instantaneous amplitude and phase spectra of GM DHP are investigated. It is noted that the technology of using amplitude spectra for DF is uninformative. This conclusion is made on the basis of a study of exclusively second-order amplitude spectra. It is known that second-order spectra do not make it possible to identify correlations of frequency components characteristic of nonlinear GM DHP. Features of the spectra of GM DHP of the order above the second are not being studied. Paper [38] investigates the features of third-order amplitude spectra for GM DHP in a laboratory chamber (LC). At the same time, it is confirmed that third-order amplitude spectra, in contrast to second-order spectra, make it possible to identify the relationships of frequency components in the spectrum characteristic of nonlinear GM DHP. It is noted that the identification of frequency connections in the dynamics spectrum significantly depends on the energy of a particular hazardous GM parameter. To get rid of this dependence is possible thru the transition to bicoherence (BC), which is invariant to the energy of the dangerous parameter. However, BC in [38] is not investigated. The study of the features of BC of an arbitrary pair of frequency components of the spectrum of GM DHP was carried out in [39]. At the same time, in works [38, 39], the features of the amplitude spectra of the third order and BC, based on the assessment of bispectra (BS), are investigated only for a selective assessment of BS. However, the traditional assessment of BS is determined by averaging a sample assessment of BS by ensemble of implementations [40, 41]. This means that the BC based on the sample assessment of the BS of GM DHP will be different from the corresponding BC on the basis of the traditional BC assessment. Thus, the unsolved part of the problem under consideration is a comparison of BC on the basis of the traditional assessment of BS and a sample assessment of BS.

3. The aim and objectives of the study

The purpose of our work is to compare the bicoherence of the bispectra assessment by the ensemble of implementations and the selective assessment of bispectra of non-stationary and nonlinear dynamics of hazardous parameters of the gas environment at intervals of absence of ignition, occurrence of ignition, and subsequent combustion of the material. The results of the comparison are of practical interest for the early detection of fires of materials in the premises to prevent the occurrence of fire.

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

– to perform a theoretical substantiation of the measure for comparing the bicoherence of the bispectra estimate by the ensemble of implementations and the selective assessment of the bispectra dynamics of the hazardous parameters of the gaseous medium at a fixed observation interval;

– to compare measures of bicoherence of bispectra estimation by ensemble of realizations and selective evaluation of bispectra for three fixed intervals of dynamics of hazardous parameters of the gaseous medium, determined by the absence of ignition, the occurrence of ignition, and combustion of test materials in the laboratory chamber.

4. The study materials and methods

The object of the study is the BC of the BS assessment by the ensemble of implementations and the BC of the selective assessment of the BS for the characteristic intervals of GM DHP with IM. The working hypothesis was the difference in BC for the specified estimates of the BS at the intervals of absence of IM, the beginning of the IM, and the interval of burning of the material. The identified differences in BC will determine which of the BC estimates is the most suitable for solving the main task of DF in order to prevent IF. The assumption aassumes that the GM DHP for real premises is similar to the pilot GM DHP in LC [38, 42]. In the laboratory experiment, the test materials were alcohol, paper, wood, and textiles. In this case, wood pine shavings were used as wood. The approximate length of wood chips was about 10 mm. The studied hazardous parameters of GM were temperature, smoke density, and CO concentration. To measure the temperature of GM, the TPT-4 sensor (Ukraine) [43] was used, for the smoke density – the IPD-3.2 sensor (Ukraine) [44], and for the concentration of CO – the Discovery sensor (Switzerland) [45]. Measurements of these hazardous parameters of GM [46] were made by sensors in the upper region of LC [47] discretely in time with an interval of 0.1 s. Discrete measurements of hazardous GM parameters in LC were stored in the computer memory for their subsequent processing. Research methods and algorithms for processing the measured data are described in detail in [37–39, 42, 47]. The studied interval of discrete measurements of GM DHP in LC was determined from count 1 to count 500 with an interval of 0.1 s. The study considered IM characteristic intervals – the absence of ignition, the onset of ignition, and combustion of materials. The interval of absence of IM was determined between 1 and 200 counts. The interval of the beginning of IM was determined from 150 to 350 counts, and the combustion interval – from 300 to 500 counts. To estimate BS for a set of implementations, each of the characteristic intervals was divided into 4 equal parts of 50 counts. A sample estimate of bispectra was determined from 50 counts for 2 of the 4 parts of each of the characteristic intervals. This method of research makes it possible to compare the BC of the bispectra assessment by the ensemble of implementations and the selective assessment of bispectra. In the course of the study, the IM in the LC was carried out at about the time of 250 counts. At the same time, the IM in the LC was produced in the following order: alcohol, paper, wood, and textiles. To restore the initial state of GM in the LC after the ignition of each test material, natural ventilation of the LC was performed for 5–7 minutes.

5. Studying the bicoherence of bispectra estimation

5. 1. Theoretical substantiation of the measure of comparison of bicoherence for the considered estimates of bispectra

It is known that BS and high-order spectra are widely used in applications to identify and recognize relationships between frequency components in the spectra of nonlinear processes [48]. For example, the use of bispectra for DF in electrical equipment is considered in [49]. At the same time, paper [50] notes that in general, BS and polyspectra serve as a reliable tool of identification of individual features of non-Gaussian processes with simultaneous suppression of additive Gaussian interference in observations. It should be noted that BS and polyspectra contain additional information about the features of processes that is absent in traditional spectra [51, 52]. In accordance with the direct method of bispectral analysis [53], the assessment of BS for multiple implementations for GM DHP at an arbitrary characteristic observation interval is represented as the following complex function of two frequency indices $h1$, $h2$:

$$Bk\left(h1,h2\right)=\frac{1}{K}\sum_{i=1}^{K}X\left(h1;Ti\right)X\left(h2;Ti\right)X^{*}\left(h1+h2;Ti\right), \qquad (1)$$

where $Bk(h1,\mathrm{h}2)$ – a function of the two frequency indices $h1$, $h2$, which determines the estimation of BS over a set of realizations at K intervals of equal duration Ti, constituting the entire interval T of the characteristic observation of GM DHP; $h1$, $h2$ – frequency indices correspond to frequencies $f1=h1/\mathrm{Ti}$ and $f2=h2/Ti$;

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

defines the Fourier image for the discrete set $\{x(k)\}$ on the interval Ti, characterized by N counts, and an arbitrary frequency index h $(0\le h\le N-1)$; * – the operator of complex conjugation. The value Ti determines the duration of this interval in seconds.

Evaluation of sample BC B($h1$, $h2$; M) for an arbitrary time interval M and a discrete set on it { $x(k)$}, following [54], will be defined as

$$B(h1,h2;M)=X(h1;M)X(h2;M)X^{*}(h1+h2;M), \qquad (2)$$

where $h1$,$h2$ – frequency indices will correspond to frequencies $a1=h1/M$ and $a2=h2/M$;

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

– defines the Fourier image for a discrete set {$x(k)$} on the interval M, characterized by a set of S counts and an arbitrary frequency index h ($0\leq h\leq S-1$).The value M determines the duration of this interval in seconds.

In this case, the Fourier image in (1) and (2) should be calculated at the intervals of stationarity of dynamics. If this condition is not met, the Fourier image will be determined with an error, the magnitude of which will depend on the degree of non-stationarity of the process at a given dynamics interval. In addition, estimates (1) and (2) are complex [55]. Therefore, it is characterized by real and imaginary parts. This means that the BC of the BS estimates (1) and (2) will be determined by the argument of the corresponding estimates. To compare the BC of estimates (1) and (2), it is necessary that the set of discrete values of the dynamics interval be the same. This means that N must be equal to S. If this condition is met, taking into account the symmetry of the BC BS, the estimates (1) and (2) can be compared on the basis of the measure determined by the mean BC in the limited range Ω of frequency indices. With this in mind, the proposed BC measures of these BS estimates (1) and (2) will be determined as:

$$KM(h1,h2)=\sum_{\Omega}\arg(K(h1,h2))/\Omega, \qquad (3)$$

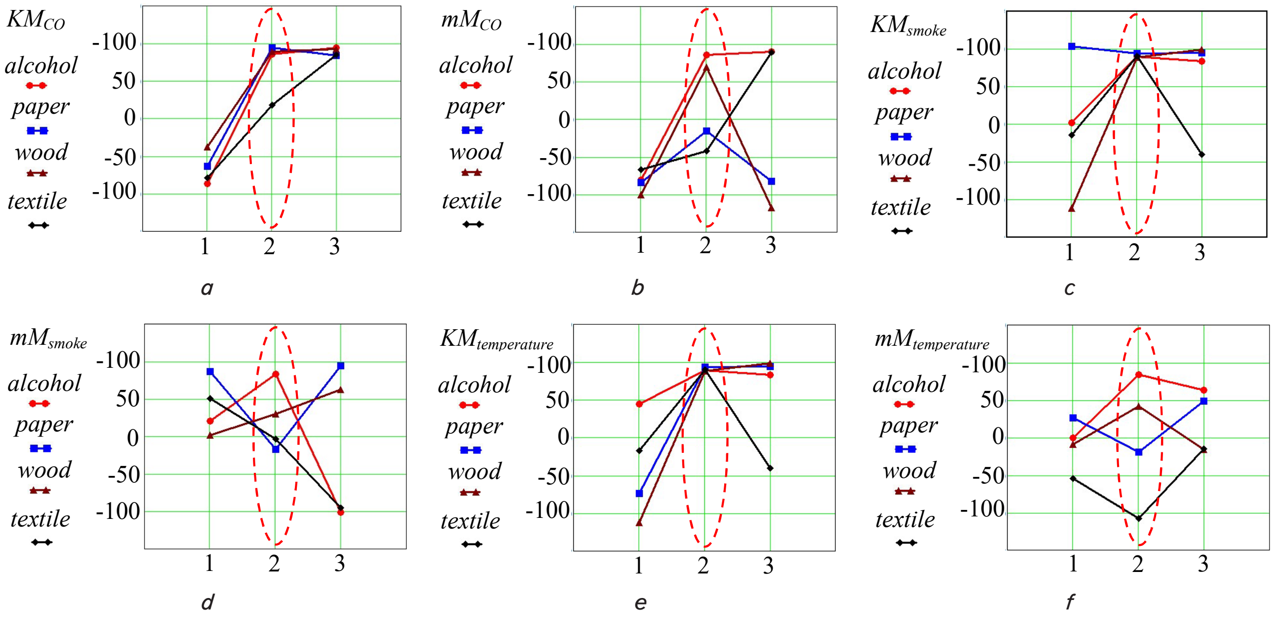
$$mM(h1,h2)=\sum_{\Omega}\arg(B(h1,h2;M))/\Omega, \qquad (4)$$

where $KM(h1,h2)$ and $mM(h1,h2)$ are BC measures for estimating BS for multiple implementations and selectively estimating BS, respectively. When selecting the region Ω of frequency indices in (3) and (4), it is necessary to take into account the specifics of determining the Fourier image. Therefore, the area Ω is limited to frequency indices that satisfy the condition $2\leq(h1,h2)\leq S/2$. It should be noted that the accuracy of the BS estimates (1) and (2) depends on the accuracy of the definition of the $X(h;Ti)$ and $X(h;M)$ spectrum, which, in turn, is inversely proportional to the durations of Ti and M of the time interval. Taking into account [56], an increase in the duration of the time interval leads to an increase in the accuracy of estimating the corresponding spectrum. Following [53, 57], for long observation intervals, the evaluations of the real and imaginary parts of BS (1) and (2) are asymptotically unalienssed and valid. BC measures (3) and (4) determine the average values of BC in a given area of frequency indices. These measures, by averaging over a given area, further reduce random errors and compare BC for different types of BS scores.

Thus, on the basis of BC measures (3) and (4), it is possible to compare them for the BS estimates under consideration at different characteristic intervals of GM DHP at IM. In other words, measures (3) and (4) numerically characterize the average interconnection of frequency components in the spectrum of GM DHP and make it possible to compare the BC of the BS estimates under consideration at characteristic intervals at IM.

5. 2. Comparison of bicoherence measures of the bispectra estimates under consideration

Procedures for obtaining and processing experimental data are discussed in detail and described in [37–39, 42, 47]. Fig. 1 shows the BC measures (3) and (4) in a given region of frequency indices from 1 to 10 for three characteristic intervals of GM DHP (CO concentration, temperature, and smoke density) – the absence of ignition (No. 1), the onset of ignition (No. 2), and subsequent combustion (No. 3) of various test materials.



a *b* *c*

d *e* *f*

Fig. 1. Measures of bicoherence of bispectra estimates of the dynamics of hazardous environmental parameters at characteristic intervals of absence of fires, presence of fires, and subsequent combustion of various test materials: *a, c, e* – in the case of evaluation for multiple implementations; *b, d, f* – in the case of selective assessment

The values of the BC measure shown in Fig. 1, for different hazardous parameters of GM, are indicated by different colors. At the same time, a dashed line of red color of the oval type highlights the characteristic interval of the beginning of the ignition of test materials.

6. Discussion of results of comparing the bicoherence of bispectra estimate

From the analysis of the data in Fig. 1 it follows that BC measures (3) and (4) numerically characterize a different average relationship for a given set of frequency indices of frequency components in the spectrum of the experimental GM DHP at given intervals. In this case, the set of frequency indices from 1 to 10 corresponds to an equivalent set of discrete frequencies from 0.2 Hz to 2 Hz. Important for DF are the intervals of absence and the beginning of ignition. Measures of BC (3) of the dynamics of the concentration of CO in the interval of absence of fires have values from –86° (for alcohol) to –37° (for wood). Under similar conditions, BC measures (4) have values ranging from –100° (for wood) to –66° (for textiles). This means that, in general, the BC measures (3) and (4) for the dynamics of the concentration of CO at the interval of absence of fires are approximately equivalent. Similar BC measures for the dynamics of temperature and smoke density of GM in the interval of absence of fires are different. Thus, to estimate the BS for a variety of implementations, the BC measure of the temperature dynamics of the GM for alcohol, paper, wood, and textiles is 1.5°, 103°, –112°, and –14°, respectively. At the same time, the BC measure of smoke density dynamics is 44.5°, –74°, –112°, and –17°. To estimate the sample BS, the measure of BC temperature dynamics is 21°, 86°, 2°, and 50°, respectively. At the same time, the BC measure of smoke density dynamics is 0°, 26°, –9°, and –54°. The maximum variation of the values of measure (3) and (4) of the dynamics of temperature and smoke density of GM in the interval of absence of fires is from 103° to –112°, and from 86° to –54°, respectively. These values of measures (3) and (4) indicate the presence of varying degrees of coupling of frequency components in the spectrum of temperature dynamics and smoke density in the interval of absence of ignition. Therefore, for the interval of absence of fires, the use of BC measures for assessing BS for a plurality of implementations and selective assessment of BS, despite different variations, have approximately the same informativeness. For the interval of the onset of fires of test materials, the values of measure (3) and (4) of the dynamics of CO concentration, temperature, and smoke density of GM differ significantly. To estimate the BS for a plurality of implementations, the value of BC measure (3) for all test materials and the dynamics of the indicated hazardous GM parameters converge to a single value close to 90°. In particular, for the dynamics of the CO concentration in the case of ignition of alcohol, paper, and wood, the values of measure (3) are 86°, 94°, and 89°, respectively. At the same time, at the interval of further ignition, the value of measure (3) tends for all materials to a value close to 90°. This indicates that when materials in the spectrum of the dynamics of the concentration of CO are ignited, the connections between the frequency components are lost, and it becomes random. When using a selective assessment of the BS for the dynamics of the concentration of CO, the values of the BC measure (4) at the interval of the onset of ignition converge to a single value close to 90°, only in the case of alcohol (85°). At the interval of the beginning of ignition, the values of the BC measure (4) for paper, wood, and textiles are –16°, 70°, and –42°, respectively. For the interval of further combustion, the values of the BC measure (4) remain close to 90° only for alcohol and textiles. In the case of burning paper and wood, the BC measures (4) are –82° and –117°, respectively. However, these values can be interpreted as close to –90° and interpreted as signs of loss of coupling of frequency components in the spectrum of CO dynamics for these materials. Approximately similar conclusions can be drawn by comparing the values of BC measures (3) and (4) for the temperature dynamics of the tested materials at characteristic ignition intervals (1–3 in Fig. 1, *c*, *d*). At the same time, for the dynamics of smoke density at characteristic intervals, the values of BC measures (3) and (4) differ. For alcohol, paper, and wood, the value of BC measure (3) at the intervals of the onset of ignition and subsequent combustion is close to 90°, which indicates a transition to random dynamics, in which there are no connections of frequency components in the spectrum. For textiles in the subsequent combustion interval, the value of measure (3) is –40° and coincides with the value of this measure for temperature dynamics. This result is explained by the difference in the nature of the combustion of textiles. The values of measure (4) at the interval of the beginning of ignition are different for each of the tested materials. For alcohol, paper, wood, and textiles, the values are 84°, –19°, 41°, and –108° respectively. The difference in the measure of BC (4) at the interval of the onset of ignition can be used in practice to recognize the type of ignition of the tested material.

Thus, on the basis of our results, test statistics in the form of BC measure (3) should be considered more suitable for the DFs of different types of materials for GM DHP. This measure is determined on the basis of the assessment of BS, obtained by averaging its sample estimates. The limitations of the study include the fact that the comparison of BC of the considered BS estimates was carried out on experimental data obtained in LC when a limited set of test materials was ignited. The noted limitation can be eliminated by using data on the real GM DHP when the materials are ignited in the premises. The direction of further development of this study can be considered the development of new types of assessments of BS and measures of the BC of GM DHP for the purpose of DF in objects of different types of premises.

7. Conclusions

1. A theoretical substantiation of the measure that makes it possible to compare bicoherences for the dynamics of hazardous parameters of the gaseous medium at an arbitrary fixed time interval has been carried out. Such a comparison is carried out on the basis of determining the assessment of bispectra for the ensemble of implementations and a selective assessment of bispectra. The basic basis of the justification is the use of two methods of direct estimation of complex bispectra for an arbitrary time interval of dynamics of hazardous parameters of the environment and the subsequent calculation of its argument. As a measure of bicoherence for these methods of estimating bispectra, it is proposed to use the average value of bicoherence for a given frequency range. This measure is integral and makes it possible to numerically

compare the bispectral bicoherence in different ways of its estimation for arbitrary time intervals of dynamics of hazardous parameters of the gaseous medium.

2. On the basis of the proposed measure, a comparison of the bicoherence of the bispectra assessment by the ensemble of realizations and the selective evaluation of bispectra is carried out. The numerical value of the measure was determined for three fixed time intervals of dynamics of hazardous parameters of the gaseous medium, covering the interval of absence of ignition, occurrence of ignition, and subsequent combustion of test materials in the laboratory chamber. According to the results of the comparison of measures, it was found that the bicoherence of the bispectra assessment for the ensemble of realizations is more effective for detecting fires. It is established that when the test materials are ignited in the chamber, the numerical value of the measure for the hazardous parameters of the gas environment and all tested materials is approximately 90°. This means that the nature of the dynamics of the dangerous parameters of the gaseous environment during fires becomes random. Therefore, this measure can be recommended as a test statistic for the early detection of fires.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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