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DEVELOPMENT OF A STRATEGY FOR USING THE BISPECTRUM OF DANGEROUS PARAMETERS TO DETERMINE AN INFORMATIVE SIGNS OF DETECTION OF MATERIALS INFLAMMATION

The object of the study is an informative sign of detecting ignition of materials in premises based on the assessment of the bispectrum of a dangerous parameter of the gas environment. The problem is to develop a strategy for using the bispectrum to determine an informative sign of detecting ignition of materials based on the observation of an arbitrary dangerous parameter of the gas environment in the premises. It is proposed to determine a new informative sign by a measure of the average degree of "order" for each frequency in the spectrum of dynamics of an arbitrary dangerous parameter of the gas environment at a fixed observation interval. The proposed informative sign was experimentally verified by studying the spectra of the average degree of "order" of the dynamics of the main dangerous parameters of the gas environment during the ignition of materials in a laboratory chamber. It was established that during the ignition of materials, the values of the average degree of "order" of the dynamics of temperature and carbon monoxide concentration for all studied frequencies of the spectrum are significantly reduced and do not exceed the value of 0.1. This indicates a loss of the average degree of "order" for all studied frequencies of the spectrum of dynamics of temperature and carbon monoxide concentration. At the same time, the value of the average degree of "order" of the dynamics of the specific optical density of smoke with respect to the studied frequencies does not change significantly. The obtained results are useful from a theoretical point of view by using the bispectrum for an informative sign of ignition and a measure of the average degree of "order" for an arbitrary dangerous parameter of the gas environment. The practical significance lies in the possibility of further improvement of existing fire protection of objects in order to prevent fires.

Keywords: *informative sign, ignition detection, bispectrum, dangerous parameters of the gas environment, premises.*

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1. Introduction

Operational information about the dynamics of dangerous parameters (DP) of the gas environment (GE) serves as one of the main components of ensuring proper fire safety in the premises of various facilities. The GE DP dynamics in the premise carries all the information necessary for the flame detection (FD) of the materials and the occurrence of a fire [1]. Temperature, CO concentration, and specific optical density of GE smoke are usually the main DPs during a fire in a premise. Therefore, the timely and reliable detection of changes in the GE DP dynamics caused by the appearance of flammable materials (FM) is considered an important direction in ensuring fire safety of premises [2]. Informative signs used in traditional fire alarm systems do not allow detecting the FM appearance before a fire occurs in the premises. Therefore, it is necessary to search for new informative signs of the GE DP dynamics, which allows reliable FM detection. Such signs can include frequency-phase connections in the GE DP dynamics. Such connections may be due to the peculiarities of complex physical processes taking place in the GE, taking into account the influence of irreversible physical and chemical processes in the materials of ignition. To identify frequency-phase relationships, it is suggested to use the apparatus of bispectral analysis, which is successfully used in the processing of various experimental data [3, 4]. In practice, the GE DP dynamics in the event of FM and fire is usually described by a random process with an a priori unknown and non-Gaussian probability distribution density. In these conditions, the phase connections between the individual components in the spectrum of the GE DP dynamics are new sources of information about the FM occurrence. In this regard, in order to ensure the fire safety of objects, it is relevant to use a bispectral analysis of the GE DP dynamics with the aim of obtaining new informative FD signs in the premises.

In [5], informative FM features are extracted from observations of one arbitrary O GE DP using multiple sensors and subsequent network processing of observations. Informative features only in the case of observation of different GE DPs are considered in [5]. In the noted works, informative features of fire detection in premises pertain to the time domain, which is usually not very sensitive to FM. The frequency domain and bispectrum are not considered for identifying new

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informative features. Currently, temporal informative features [5, 6] for FD have already been approved in EN and ISO standards. Thus, in [7], informative features in the time domain for CO and GE temperature observations are used jointly for FD. In [8], the use of temporal informative features for FD indoors with simultaneous monitoring of the state of GE DP observation sensors is considered. In [9], FD based on temporal informative features for CO observations should be carried out jointly with one or more temperature sensors. However, in [7–9], the temporary informative features of the GE DP are used to detect a fire when the absolute DP values significantly exceed their background values. For this reason, they do not allow the FD of materials when the absolute GE DP values are comparable with their background values. In [10], it is proposed to use informative features of the dynamics of GE smoke to detect a fire.

However, they have low detection reliability, which significantly depends on the GE temperature [11]. For this reason, smoke informative features [12] are usually used together with temperature informative features [13]. In this regard, advanced fire alarm systems use a set of informative features in the time domain for various GE DPs [14]. At the same time, the use of a set of time informative features does not allow the FD of materials. Informative features of the GE DPs in the time domain during plantation wood combustion in the form of heat release rate from combustion intensity are studied in [15]. The influence of heat release rate on wood combustion intensity is studied in [16]. However, in [16], the studies are limited to only average informative features of heat release rate and combustion intensity. Similar studies for organic glass and cypress are performed in [17]. However, in [16, 17] there are no results of studying informative features for third-order spectra and GE DP bispectra capable of revealing features of complex dynamics of real DPs during FD in premises. In [18], instantaneous amplitude and phase spectra of the GE DP dynamics of premises in the frequency domain are investigated. It is noted that the amplitude frequency spectra have insufficient informative FD features. The results of fire tests taking into account various background effects without proposing informative FM features are considered in [19]. However, it is shown that for a reliable FM it is necessary to take into account the dynamics of the CO concentration together with the dynamics of the specific optical density of the smoke of the GE. In this case, informative FD features are not considered.

In [20] the results of an experimental study of the mutual relationship between different GE DPs under FM are presented. However, such a relationship is estimated by mutual correlation, which reveals only the degree of linear relationship. Spectral and correlation characteristics higher than the second order, capable of revealing nonlinear relationships in the dynamics of the GE DPs under FM are not considered. The third-order amplitude spectra of the GE DP dynamics are considered in [21]. It is shown that such an approach allows revealing the nonlinear relationship of the frequency components in the spectrum of the GE DP dynamics. However, the degree of nonlinear relationship of the frequency components (coherence) significantly depends on the energy of a specific DP. At the same time, the degree of nonlinear relationship of the frequency components in the third-order phase spectrum, which does not depend on the energy of the observed DP, is not considered. Features of the average bicoherence of the frequency components in the spectrum of the GE DP dynamics under FM are considered in [22]. It is noted that the average value of bicoherence can be considered as a possible informative FM feature. The disadvantage of this informative feature is its alternating nature, which complicates the interpretation of the degree of order or chaos of the observed GE DP dynamics during VM. The use of the empirical cumulative distribution function of the current recurrence of the GE DP state as a possible informative FM feature is considered in [23]. However, the use of this feature is associated with the implementation of a complex computational procedure. In this case, the informative feature [23] belongs to the time domain of observation. In [24], it is proposed to select the probability of the absence of recurrence of increments of the state vector of dangerous GE DP determined on the basis of the empirical cumulative distribution function as an informative feature.

However, the implementation of this informative feature is associated with complex calculations, which limits its use in practice. Thus, from the point of view of the informative FD feature, the use of the bispectrum of the GE DP dynamics for this purpose is new. At the same time, the use of the bispectrum of the GE DP dynamics for the purpose of finding informative FM features has not been sufficiently studied. Based on the bispectrum, non-traditional informative FM features can be determined, in the form of the degree of order or disorder (chaos) of the GE DP dynamics. However, it should be noted that the use of the degree of order or disorder (chaos) of the observed GE DP dynamics in premises as a new informative FM feature has been practically not studied. In this regard, the strategy of using the bispectrum to assess the degree of order or disorder (chaos) of the GE DP dynamics in the presence and absence of the FM is of particular interest. Therefore, an important and unresolved part of the FD problem in premises should be considered the substantiation of a new informative feature based on the use of the bispectrum of the GE DP dynamics, numerically characterizing the degree of DP order in the absence and presence of FM in the premise.

The aim of research is to develop a strategy for using the bispectrum to determine the informative feature of combustion, characterizing the degree of order of the dynamics of an arbitrary dangerous parameter of the gas environment, as well as to experimentally verify the informative feature during the ignition of test materials in a laboratory chamber. The use of the proposed informative feature of the GE DP dynamics will allow timely FD of materials for the purpose of their prompt extinguishing and eliminating the threat of fire in the premises of objects.

2. Materials and Methods

The object of research is the informative feature of the FD of materials based on the assessment of the bispectrum of the dynamics of an arbitrary GE DP in the premise. The rationale for the new informative FD feature based on the bispectrum was based on the fact that the ignition of any material is accompanied by certain changes in the physical properties of the material itself, as well as the GE DP in the premise. Usually, during a FM, a heat flow, toxic combustion products and other dangerous substances are released into the GE of the premise [25]. This means that the FD can be carried out based on the corresponding informative features of the dynamics of the GE DP, sensitive to the initial FM stage. Considering the complexity and uncertainty of the physicochemical reactions occurring during FM, as well as the weak level of the indicated processes at the FM beginning, it is not possible to use traditional informative features of the GE DP dynamics for the FD. Under these conditions, the bispectral approach offers a way to obtain additional information on the phase correlation of the corresponding frequencies in the spectrum of the GE DP dynamics [26]. In general, higher-order spectra are an effective tool for identifying hidden connections between different frequencies in the spectrum of processes of different nature [27]. In [28], it is noted that they allow identifying the features of non-Gaussian processes observed against the background of additive Gaussian interference. The use of a third-order spectrum to determine the informative FD feature of electrical equipment is considered in [29]. Third-order spectra are often called bispectra. Bispectra allow identifying hidden features of nonlinearity of the analyzed processes caused by quadratic transformations. In this case, the estimate of the bispectrum $B(h1, h2; T)$ for a discrete set $\{x(k)\}$ of process values observed over an arbitrary time interval T, following [30], will be defined as

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

where $B(h1, h2; T)$ – a function of variables $h1$, $h2$, which have the meaning of frequency indices, and the duration T of an arbitrary observation interval; $X(h;T)=\sum_{k=0}^{N-1} x(k)\exp(-j2\pi hk/N)$, $(0 \le k \le N-1)$ – the Fourier transform of a discrete set $\{x(k)\}$ for the frequency index h $(0 \le h \le N-1)$; * is the complex conjugation operator.

The frequency index h corresponds to the frequency $f = h/T$ in Hz, where the value T is measured in seconds. It should be noted that the bispectrum estimate (1) is a complex value. This means that it is determined by the real $Re[B(h1, h2; T)]$ and imaginary $Im[B(h1, h2; T)]$ parts of the bispectrum. In this case, the real part carries information about the time-reversible part of the set $\{x(k)\}$, and the imaginary part – about the irreversible part of this set. Then the estimate of the phase of the bispectrum (1) will be determined by the function $\varphi(h1, h2; T)$ of the form

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

Function (2), being an estimate of the phase of the bispectrum (1), carries information about the hidden phase relationship of frequencies for the corresponding frequency indices in the spectrum of the set $\{x(k)\}$. In this case, the set of values of function (2) belongs to the interval $(0, 2\pi)$. At the same time, function (2) serves as a quantitative estimate of the ratio of the irreversible and reversible parts of the set $\{x(k)\}$ of the observed process. This means that function (2) can be considered as a quantitative estimate of the ratio between the "disorder" and "order" of the set $\{x(k)\}$ of the observed process. For the convenience of using function (2) as a new informative feature for an arbitrary GE DP for the FD purpose, numerically characterizing the degree of "order" of the set $\{x(k)\}$, it is possible to introduce a measure defined as

$$\boldsymbol{M}(h1,h2;T)=\cos\left[\varphi(h1,h2;T)\right]^2. \quad (3)$$

Measure (3) depends on the corresponding frequency indices and the duration of the observation interval of the set $\{x(k)\}$. Unlike function (2), the values of measure (3) lie in the interval (0, 1).

This means that the values of measure (3) equal to zero will correspond to the absolute "disorder" or "chaos" of the set $\{x(k)\}$. In this case, the values of measure (3) equal to one will correspond to the absolute "order" of the set $\{x(k)\}$. Intermediate values of measure (3) will determine different degrees of "order" of the set $\{x(k)\}$ of observations. This means that the values of measure (3) equal to zero will correspond to the values of the phase of the bispectrum $\pi/2$, which characterize the incoherence for an arbitrary pair of frequency components of the spectrum of the set $\{x(k)\}$ under a quadratic transformation. This fact can be interpreted as absolute "disorder" or "chaos" for the specified pairs of frequency components of the spectrum $\{x(k)\}$. In this case, the values of measure (3) equal to one will correspond to zero values of the bispectrum phase, which characterize the coherence for an arbitrary pair of frequency components of the spectrum of the set $\{x(k)\}$ under a quadratic transformation. In this case, the specified pair of frequency components is characterized by coherence under quadratic transformations, which corresponds to the absolute "order" for the considered pairs of frequency components of the spectrum $\{x(k)\}$. In this case, intermediate values of measure (3) will determine different degrees of "order" for arbitrary pairs of frequency components of the set $\{x(k)\}$ of observations. The accuracy of measure (3) will be determined by the accuracy of the estimate $X(h; T)$, which is inversely proportional to the duration T of the observation interval of the set $\{x(k)\}$ [31]. For large values of T (large N), the estimates of the real and imaginary parts of the bispectrum (1) turn out to be asymptotically unbiased and consistent [3, 32]. The new informative FD feature in the form of measure (3) will determine the estimate of the degree of "order" for an arbitrary pair of frequency components of the spectrum of the set $\{x(k)\}$ of observations under quadratic transformations. In this case, the estimate of the degree of "order" will be numerically determined by the value of the phase coupling (coherence) for the triple of frequencies of the spectrum of GE DP observations, corresponding to the frequency indices $h1$, $h2$ and $h1 + h2$. For an arbitrary number N of discrete values of the set $\{x(k)\}$, the domain of definition for each of the frequency indices $h1$ or $h2$ will be limited by the interval $(1, N/2)$. The measure of the degree of "order" (3) determines the value of phase coupling between three arbitrary frequencies in the spectrum of the set $\{x(k)\}$, which correspond to arbitrary frequency indices $h1$, $h2$ and $h1 + h2$. This means that measure (3) will allow to estimate the degree of "order" (degree of invertibility) of the set $\{x(k)\}$ observed on the interval T of an arbitrary GE DP. However, measure (3) for a fixed T is a function of two variables $h1$, $h2$, which makes it inconvenient to use as an informative FD feature. A more promising measure is one related to (3), but of a different type

$$DCP_{h1}=\sum_{h2=1}^{N/2}\boldsymbol{M}(h1,h2;T)2/N. \quad (4)$$

This measure is an estimate of the average degree of "order" for each frequency index $h1$ taking into account all particular degrees of "order" of frequency indices $h2$ in the spectrum of the set $\{x(k)\}$ of observations of an arbitrary GE DP. In other words, measure (4) is a spectrum of average degrees of "order" for the set $\{x(k)\}$ of observations of an arbitrary GE DP. Measure (4) is an estimate of the informative FD feature in the spectral region determined on the basis of the estimate of the bispectrum (1) of an arbitrary observed GE DP. This means that, based on measure (4), it is possible to study the spectra of the average degree of "order" for the set $\{x(k)\}$ of observations on characteristic intervals. The verification of the proposed informative FD feature was carried out experimentally by studying the measure (4) of the set $\{x(k)\}$ of observations for the main GE DP on the intervals of reliable absence and presence of ignitions of test materials (TM). For this purpose, a laboratory chamber simulating a non-hermetic premise was created. The dimensions of the chamber were: 1500 × 1000 × 500 mm. In the upper part of the chamber, above the source of TM ignition, sensors were placed to monitor the temperature, specific optical density of smoke and CO concentration [33]. The GE temperature in the chamber was monitored using a DS18B20 sensor (USA), the specific optical density of smoke – using an IPD-3.2 sensor (Ukraine) and the CO concentration – using a Discovery sensor (Switzerland) [34]. The results of monitoring the output signals of the corresponding sensors served as research materials. Observations were made at intervals of reliable absence and presence of TM ignition. In the study, alcohol, paper (crumpled A4 sheet), wood (shavings) and textile (a piece of cotton fabric 50 x 100 mm) were selected as TM. The specified TM are characterized by different specific mass burnout rates [35]. Observations of the output signals of the sensors studied by the GE DP were recorded discretely in time with a sensor polling interval of 0.1 seconds. The obtained discrete values of the output signals of the corresponding sensors were determined by sets $\{x(k)\}$ of observations and stored in the computer memory for processing. The corresponding set $\{x(k)\}$ consisted of a sequential in time data set $x1, x2, x3, ..., xN$, where N was determined by the end of the specified observation interval. In this case, it is proposed that the value of measure (4) equal to one be considered a sign of absolute "order" for the set $\{x(k)\}$ of GE DP observations, and equal to zero – absolute "disorder" or the absence of "order" – "chaos". The value of measure (4) equal to 0.5 in this case will be a sign of instability of the set $\{x(k)\}$ of observations of an arbitrary GE DP.

3. Results and Discussion

The study of measure (4) for the set $\{x(k)\}$ of observations of temperature, specific optical density of smoke and GE CO concentration in a laboratory chamber during TM combustion was carried out for

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a fixed number of frequencies corresponding to 20 frequency indices at $N = 100$ ($T = N\,0.1$ s). This means that an arbitrary frequency index $g1$ from the set (1, ..., 20) will correspond to the frequency $f1 = g1 \times 10/N$, and the index $g2$ from the set (1, ..., 20) will correspond to the frequency $f2 = g2 \times 10/N$. For this particular case, measure (4) will be defined as

$$DCP1_{g1} = \sum_{g2=1}^{20} M(g1, g2; T)/20. \qquad (5)$$

Measure (5) allows to investigate the estimate of the average degree of "order" for each value of the frequency index $g1$ in the interval from 1 to 20 of the set $\{x(k)\}$ of observations corresponding to the GE DP in the laboratory chamber. Based on measure (5), it is possible to investigate the spectrum of the average degree of "order" taking into account all the degrees of "order" for the remaining frequency indices. Therefore, the study of the influence of ignition on the spectrum of the average degree of "order" of the set $\{x(k)\}$ of observations for the corresponding GE DP can be performed based on observations of the corresponding sets on the intervals of reliable absence and presence of FM. Fig. 1 shows the results of the study of the spectra of the average degree of "order" for the set $\{x(k)\}$ of observations of temperature, specific optical density of smoke and concentration of carbon monoxide GE in the laboratory chamber on the intervals of reliable absence and presence of TM ignition. The curves in Fig. 1 red correspond to the observations for alcohol, blue – paper, green – wood, and violet – textile. The results in Fig. 1 show that the spectra of the average degree of "order" of the studied GE DP are non-uniform both in the absence and presence of TM ignition. The value of the measure (4) less than one indicates, in general, the non-linearity of the GE DP dynamics. The exception are the spectra of the average degree of "order" for the GE temperature in the chamber in the absence of alcohol and paper ignition (Fig. 1, *a*), which are uniform and equal to one. This indicates that the dynamics of the GE temperature in the laboratory chamber in the absence of alcohol and paper ignition has a hidden phase relationship (coherence) of the frequency components in the spectrum for the corresponding frequency triplets, and also confirms its sufficient stability and quadratic non-linearity of the transformations.

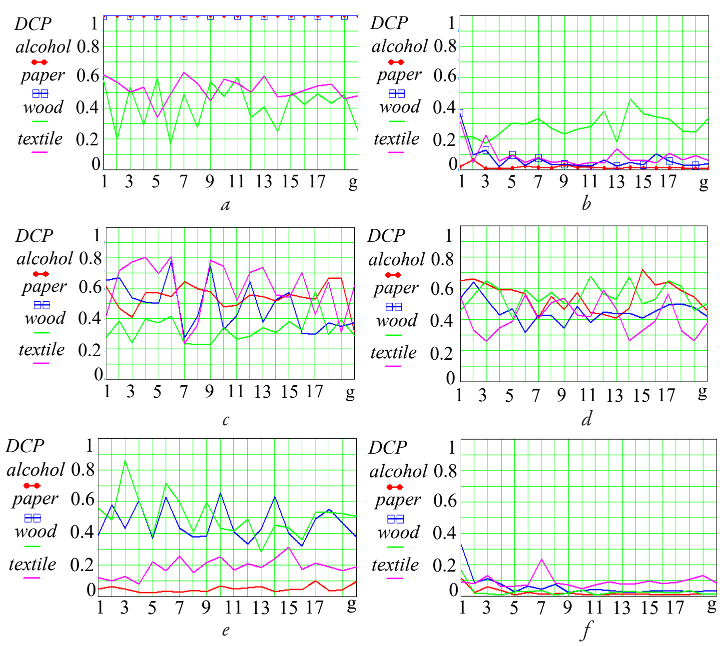

Fig. 1. Experimental spectra of the average degree of "order" of dangerous parameters of the gas environment in the absence and presence of material combustion: *a* – temperature in the absence of combustion; *b* – temperature during combustion; *c* – specific optical density of smoke in the absence of combustion; *d* – specific optical density of smoke during combustion; *e* – CO concentration in the absence of combustion; *f* – CO concentration during combustion

In contrast, in the absence of combustion of wood and textile (Fig. 1, *a*, green and violet curves, respectively), the spectrum of the average degree of "order" for the GE temperature is of an uneven random nature. In this case, the value of the spectrum of the average degree of "order" does not exceed 0.6, which indicates a more complex nonlinear nature of the GE temperature dynamics. This can be explained by the specifics of the study, in which the FM in the chamber was carried out sequentially, and after the combustion of each of the materials at the end of the observation interval, natural ventilation of the chamber was carried out for 5–7 minutes in order to restore the GE DP in the chamber. Perhaps, this time was insufficient for complete restoration of the dynamics of the chamber GE temperature after the combustion of paper and wood. The results in Fig. 1, *c*, *e* also take into account the FM sequence and correspond to the ventilation time of the chamber for 5–7 minutes. However, these results indicate the important fact that the dynamics of temperature, specific optical density of smoke and carbon monoxide concentration of the GE chamber in the interval without FM are characterized by unequal spectra of the average degree of "order". This indicates differences in the complex hidden mechanisms of interaction of the combustion materials with the studied GE DP in the chamber. When TM ignites in the chamber, the results shown in Fig. 1, *b*, *f*, show that the values of the average degree of "order" of the studied GE DP for the dynamics of temperature and carbon monoxide concentration for frequency indices do not exceed 0.1. This means that when materials ignite, the average degree of "order" of the dynamics of temperature and carbon monoxide concentration is significantly reduced and loses "order", approaching "chaos". At the same time, the average degree of "order" of the optical density dynamics of smoke with FM in the studied interval changes insignificantly. Hence, the conclusion follows that the proposed FD feature in the form of the value of the average degree of "order" is advisable to apply to the dynamics of temperature and CO concentration of the GE. The proposed FD feature can be used in practice when developing new and improving existing fire automation systems and tools capable of FD by a significant reduction in the average degree of "order" of GE DP observations. The limitation of this research is that the obtained results of checking the proposed FD feature were performed based on observing a limited GE DP number at two intervals of a fixed duration of reliable absence and presence of TM ignitions in a laboratory chamber. In this regard, it is advisable to expand further studies in the direction of checking the proposed FD feature in the case of fire tests in real premises for different fire loads.

4. Conclusions

A strategy has been developed for using a bispectrum to determine a new informative feature of material ignition in the form of a measure of the degree of "order" for the observed dynamics of an arbitrary dangerous parameter of the gas environment over a fixed time interval. For the purpose of practical use of this informative feature of ignition, a measure of the average degree of "order" for each frequency component of the spectrum of the observed dynamics of an arbitrary dangerous parameter of the gas environment has been proposed. This measure is an spectrum estimate of the average degree of "order" of the observed dynamics of the gas environment dangerous parameters. An experimental verification of the proposed informative FD feature has been performed based on a study of the spectra of the average degree of "order" of the dynamics of the main gas environment dangerous parameters during ignition of test materials in a laboratory chamber. It has been established that during ignitions, the values of the average degree of "order" of the studied gas environment dangerous parameters of the dynamics of temperature and carbon monoxide concentration of the gas environment for the studied frequency components of the dynamics spectrum decrease and do not exceed 0.1. This means that ignition causes a decrease in the average degree of "order" of the temperature dynamics and carbon monoxide concentration, bringing it closer to "chaos". At the same time, the average degree of "order" of the smoke optical density dynamics during ignition of materials in the studied interval changes insignificantly. It is shown that the proposed FD feature in the form of the value of the average degree of "order" for the frequency components of the spectrum is appropriate to use for the temperature dynamics and carbon monoxide concentration of the gas environment. In practice, the proposed FD feature can be used in the development of new means and systems of fire automation to prevent the development of fire in the premises of objects.

Conflict of interest

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

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the presented work.

References

1. Pospelov, B., Rybka, E., Polkovnychenko, D., Myskovets, I., Bezuhla, Y., Butenko, T. et al. (2023). 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. *Eastern-European Journal of Enterprise Technologies, 2 (10 (122))*, 14–21. https://doi.org/10.15587/1729-4061.2023.276779
2. Sadkovyi, V., Andronov, V., Semkiv, O., Kovalov, A., Rybka, E., Otrosh, Y. et al. (2021). *Fire resistance of reinforced concrete and steel structures*. Kharkiv: PC TECHNOLOGY CENTER, 180. https://doi.org/10.15587/978-617-7319-43-5
3. Nikias, C. L., Raghuveer, M. R. (1987). Bispectrum estimation: A digital signal processing framework. *Proceedings of the IEEE, 75 (7)*, 869–891. https://doi.org/10.1109/proc.1987.13824
4. Totsky, A. V., Zelensky, A. A., Kravchenko, V. F. (2015). *Bispectral Methods of Signal Processing: Applications in Radar, Telecommunications and Digital Image Restoration*. Berlin, München, Boston: De Gruyter, 203. https://doi.org/10.1515/9783110368888
5. Cheng, C., Sun, F., Zhou, X. (2011). One fire detection method using neural networks. *Tsinghua Science and Technology, 16 (1)*, 31–35. https://doi.org/10.1016/s1007-0214(11)70005-0
6. Ding, Q., Peng, Z., Liu, T., Tong, Q. (2014). Multi-Sensor Building Fire Alarm System with Information Fusion Technology Based on D-S Evidence Theory. *Algorithms, 7 (4)*, 523–537. https://doi.org/10.3390/a7040523
7. *BS EN 54-30:2015. Fire detection and fire alarm systems – Part 30: Multi-sensor fire detectors. Point detectors using a combination of carbon monoxide and heat sensors* (2015). Available at: https://standards.iteh.ai/catalog/standards/cen/ed5ec3f0-1e86-488f-93e4-bffd1e60da24/en-54-30-2015?srsltid=AfmBOoqsU4jyvPf8I3oOQMPUUTVC2HxSmzDcpEJc34wrJALkOWr7MTT9
8. *BS EN 54-31:2014. Fire detection and fire alarm systems – Part 31: Multi-sensor fire detectors. Point detectors using a combination of smoke, carbon monoxide and optionally heat sensors* (2014). Available at: https://standards.iteh.ai/catalog/standards/cen/40570bab-0b10-4d86-aa64-3cce3be84086/en-54-31-2014-fpra1-2015?srsltid=AfmBOooz9291E5XcWrPoh1QLlaxEt9Wq_F60n-NBofLV7B-SHS6_iepZ
9. *ISO 7240-8:2014. Fire detection and alarm systems. Part 8: Point-type fire detectors using a carbon monoxide sensor in combination with a heat sensor* (2014). International Organization for Standardization.
10. Aspey, R. A., Brazier, K. J., Spencer, J. W. (2005). Multiwavelength sensing of smoke using a polychromatic LED: Mie extinction characterization using HLS analysis. *IEEE Sensors Journal, 5 (5)*, 1050–1056. https://doi.org/10.1109/jsen.2005.845207
11. Chen, S.-J., Hovde, D. C., Peterson, K. A., Marshall, A. W. (2007). Fire detection using smoke and gas sensors. *Fire Safety Journal, 42 (8)*, 507–515. https://doi.org/10.1016/j.firesaf.2007.01.006
12. Shi, M., Bermak, A., Chandrasekaran, S., Amira, A., Brahim-Belhouari, S. (2008). A Committee Machine Gas Identification System Based on Dynamically Reconfigurable FPGA. *IEEE Sensors Journal, 8 (4)*, 403–414. https://doi.org/10.1109/jsen.2008.917124
13. Skinner, A. J., Lambert, M. F. (2006). Using Smart Sensor Strings for Continuous Monitoring of Temperature Stratification in Large Water Bodies. *IEEE Sensors Journal, 6 (6)*, 1473–1481. https://doi.org/10.1109/jsen.2006.881373
14. Cheon, J., Lee, J., Lee, I., Chae, Y., Yoo, Y., Han, G. (2009). A Single-Chip CMOS Smoke and Temperature Sensor for an Intelligent Fire Detector. *IEEE Sensors Journal, 9 (8)*, 914–921. https://doi.org/10.1109/jsen.2009.2024703
15. Wu, Y., Harada, T. (2004). Study on the Burning Behaviour of Plantation Wood. *Scientia Silvae Sinicae, 40*, 131.
16. Ji, J., Yang, L., Fan, W. (2003). Experimental Study on Effects of Burning Behaviours of Materials Caused by External Heat Radiation. *JCST, 9*, 139.
17. Peng, X., Liu, S., Lu, G. (2005). Experimental Analysis on Heat Release Rate of Materials. *Journal of Chongqing University, 28*, 122.
18. Pospelov, B., Rybka, E., Samoilov, M., Morozov, I., Bezuhla, Y., Butenko, T. et al. (2022). Defining the features of amplitude and phase spectra of dangerous factors of gas medium during the ignition of materials in the premises. *Eastern-European Journal of Enterprise Technologies, 2 (10 (116))*, 57–65. https://doi.org/10.15587/1729-4061.2022.254500
19. Heskestad, G., Newman, J. S. (1992). Fire detection using cross-correlations of sensor signals. *Fire Safety Journal, 18 (4)*, 355–374. https://doi.org/10.1016/0379-7112(92)90024-7
20. Gottuk, D. T., Wright, M. T., Wong, J. T., Pham, H. V., Rose-Pehrsson, S. L., Hart, S. et al. (2002). *Prototype Early Warning Fire Detection Systems: Test Series 4 Results*. NRL/MR/6180-02-8602. Naval Research Laboratory.
21. Pospelov, B., Rybka, E., Savchenko, A., Dashkovska, O., Harbuz, S., Naden, E. et al. (2022). Peculiarities of amplitude spectra of the third order for the early detection of indoor fires. *Eastern-European Journal of Enterprise Technologies, 5 (10 (119))*, 49–56. https://doi.org/10.15587/1729-4061.2022.265781
22. Pospelov, B., Andronov, V., Rybka, E., Chubko, L., Bezuhla, Y., Gordiichuk, S. et al. (2023). Revealing the peculiarities of average bicoherence of frequencies in the spectra of dangerous parameters of the gas environment during fire. *Eastern-European Journal of Enterprise Technologies, 1 (10 (121))*, 46–54. https://doi.org/10.15587/1729-4061.2023.272949
23. Pospelov, B., Andronov, V., Rybka, E., Bezuhla, Y., Liashevska, O., Butenko, T. et al. (2022). Empirical cumulative distribution function of the characteristic sign of the gas environment during fire. *Eastern-European Journal of Enterprise Technologies, 4 (10 (118))*, 60–66. https://doi.org/10.15587/1729-4061.2022.263194
24. Sadkovyi, V., Pospelov, B., Rybka, E., Kreminskyi, B., Yashchenko, O., Bezuhla, Y. et al. (2022). Development of a method for assessing the reliability of fire detection in premises. *Eastern-European Journal of Enterprise Technologies, 3 (10 (117))*, 56–62. https://doi.org/10.15587/1729-4061.2022.259493
25. Popov, O., Kovach, V., Iatsyshyn, A., Lahoiko, A., Ryzhchenko, O., Dement, M. (2023). Features Function of Radiation Monitoring System World's Countries of Developed Nuclear Energy. *Systems, Decision and Control in Energy V*. Cham: Springer, 471–497. https://doi.org/10.1007/978-3-031-35088-7_25
26. Jeong, J. (2004). EEG dynamics in patients with Alzheimer's disease. *Clinical Neurophysiology, 115 (7)*, 1490–1505. https://doi.org/10.1016/j.clinph.2004.01.001
27. Saeed, M., Alfatih, S. (2013). Nonlinearity detection in hydraulic machines utilizing bispectral analysis. *TJ Mechanical engineering and machinery*, 13–21.
28. Yang, B., Wang, M., Zan, T., Gao, X., Gao, P. (2021). *Application of Bispectrum Diagonal Slice Feature Analysis in Tool Wear States Monitoring*. Research Square. https://doi.org/10.21203/rs.3.rs-775113/v1
29. Yang, K., Zhang, R., Chen, S., Zhang, F., Yang, J., Zhang, X. (2015). Series Arc Fault Detection Algorithm Based on Autoregressive Bispectrum Analysis. *Algorithms, 8 (4)*, 929–950. https://doi.org/10.3390/a8040929
30. Cui, L., Xu, H., Ge, J., Cao, M., Xu, Y., Xu, W. et al (2021). Use of Bispectrum Analysis to Inspect the Non-Linear Dynamic Characteristics of Beam-Type Structures Containing a Breathing Crack. *Sensors, 21 (4)*, 1177. https://doi.org/10.3390/s21041177
31. Max, J. (1981). *Methodes et techniques de traitement du signal et applications aux mesures physiques: Tome I. Principes généraux et méthodes classiques. Troisième édition revue et augmentée*. Paris: Masson, 302.
32. Mohankumar, K. (2015). *Implementation of an underwater target classifier using higher order spectral features*. [PhD thesis].
33. Dubinin, D., Cherkashyn, O., Maksymov, A., Beliuchenko, D., Hovalenkov, S., Shevchenko, S. et al. (2020). Investigation of the effect of carbon monoxide on people in case of fire in a building. *Sigurnost, 62 (4)*, 347–357. https://doi.org/10.31306/s.62.4.2

34. Optical/Heat Multisensor Detector (2019). *Discovery, 1*, 4.
35. Hulse, L. M., Galea, E. R., Thompson, O. F., Wales, D. (2020). Perception and recollection of fire hazards in dwelling fires. *Safety Science, 122*, 104518. https://doi.org/10.1016/j.ssci.2019.104518

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