UDC 519.004:621.833
DOI: 10.15587/1729-4061.2025.327905

MULTI-LEVEL PROCESSING OF VIBROACOUSTIC SIGNALS FOR IMPROVING THE DIAGNOSTICS OF GAS TURBINE ENGINES

Nadiia Bouraou
Doctor of Technical Sciences, Professor, Head of Department
Department of Computer-Integrated Optical and Navigation Systems*
Olha Pazdrii
Corresponding author
PhD, Assistant
Department of Computer-Integrated Optical and Navigation Systems*
E-mail: olgapazdri@gmail.com
Oleksandr Povcshenko
PhD, Assistant
Department of Automation and Non-Destructive Testing Systems*
*National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Beresteiskyi ave., 37, Kyiv, Ukraine, 03056

The object of this study is the process of monitoring the technical condition of an aircraft gas turbine engine (GTE). One of the most dangerous causes of accidents is damage caused by foreign objects, in particular small metal particles, hailstones, bolts, fuselage fragments, etc., entering the engine turbine during flight or during takeoff and landing.

The task addressed was to improve the methods of gas turbine engine vibroacoustic diagnostics, which would increase its sensitivity to small changes in diagnostic signals caused by the ingress of small foreign objects into the engine turbine. To solve this problem, it has been proposed to use multi-level processing of vibration signals obtained as a result of physical modeling of the rotating system (RS) and simulation of the ingress of small foreign objects.

Multi-level processing combines the use of time-frequency, bispectral, and fractal analysis methods to determine the quantitative integrated diagnostic indicator – Minkowski dimensionality. The following average values of Minkowski dimensionality were obtained for the estimates of the bispectral modulus: without external influence – 1.075; ingress of small foreign objects – 1.01; friction of the blades against a foreign object as a result of its ingress into the RS turbine – 1.21.

It has been established that an increase in the Minkowski dimensionality indicates the development of an operational disturbance caused by the ingress of foreign objects, even very small ones.

This paper reports experimental confirmation of the effectiveness of using multi-level processing of vibration signals for diagnosing operational disturbances due to the ingress of foreign objects into RS.

It has been established that multi-level processing makes it possible to detect hidden trends in a noisy signal that are difficult to detect using conventional processing methods

Keywords: gas turbine engine, foreign object ingestion, signal processing, fractal analysis

Received 06.02.2025
Received in revised form 03.04.2025
Accepted 17.04.2025
Published 30.04.2025

***How to Cite:** Bouraou, N., Pazdrii, O., Povshenko, O. (2025). Multi-level processing of vibroacoustic signals for improving the diagnostics of gas turbine engines. Eastern-European Journal of Enterprise Technologies, 2 (5 (134)), 25–33. https://doi.org/10.15587/1729-4061.2025.327905*

1. Introduction

Aviation gas turbine engines (GTEs) are complex rotating systems operating under constant dynamic loads. One of the key factors in ensuring reliability and flight safety is continuous monitoring and diagnostics of the engine's technical condition [1]. However, despite the high level of development and implemented measures to ensure flight safety, aviation accidents continue to occur. Over the past year alone, more than 75 such incidents have been recorded. According to statistics, most aviation accidents occur during landing or takeoff. One of the most common causes of such accidents is the formation and development of crack-like damage in the rotating elements of GTE such as the shaft, turbine blades, and compressor, during operation [1, 2]. These damages can cause non-localized engine failures and have catastrophic consequences.

No less dangerous and common operational violations are the ingress of foreign objects (IFOs) [3]. Foreign objects (FOs) such as birds, fuselage debris, hail, etc., can enter the engine turbine during flight, causing potential malfunctions. However, it is much more common for FOs to enter the turbine during takeoff or landing on the runway. These may include landing gear components, tire fragments, cleaning rags, clothing, tools, etc. [4]. There is also a risk of very small objects such as gravel, small stones, metal bolts, hail, sand, etc. entering the turbine [4].

In the case of IFOs, early diagnosis of such operational violations is critically important for ensuring safe and efficient engine operation. This allows for timely detection of IFOs in the engine turbine and making operational decisions to prevent possible aviation incidents. Modern onboard GTE condition monitoring systems implement the principles of structural monitoring and use an integrated approach involving various diagnostic methods [1]. In particular, vibration, vibroacoustic, and thermodynamic monitoring are used to detect IFOs in the engine turbine. Vibration and vibroacoustic monitoring have such advantages as ease of signal conversion into electrical form, high information content, and the possibility of application during operation, which provides automated diagnostics [5–9].

For real-time vibration monitoring and detection of operational damage to GTE components, diagnostic information is obtained from several vibration sensors that monitor the level of vibrations in different parts of the engine (compressor, turbine, etc.) [8]. The obtained diagnostic information is represented in the form of noise-like multicomponent signals. Such signals are difficult to analyze by conventional processing methods to detect the slightest changes and diagnostic signs caused by the appearance of operational disturbances of GTE or damage to its rotating elements. Therefore, improving the methods of vibroacoustic diagnostics to increase the efficiency of detecting the ingress of small foreign objects into GTE by using multilevel signal processing is a relevant task.

2. Literature review and problem statement

In works [9, 10], multilevel processing of vibroacoustic signals was proposed for early identification of such operational violations of the gas turbine engine as a small imbalance and crack-like damage to the blade at the initial stages of occurrence, respectively. The use of multilevel processing for early diagnosis of this type of damage was effective. However, in [9, 10], experimental studies were not conducted for diagnosing especially small FOs.

In paper [11], experimental studies of IFOs in gas turbine engines were conducted. An analysis of the impact of damage as a result of IFO was conducted and it was found that even small FOs provoke the appearance of microcracks, which, with development, can cause serious consequences. It was shown that the degree of damage depends on the speed and angle of contact of FOs with the engine turbine blades. However, in [11], it is not disclosed which diagnostic features can be used for early diagnosis of IFOs in the engine, which is important for the development of an automated system.

The research reported in [12] is aimed at designing systems for detecting FOs in turbofan engines. Information from various sensors of the on-board engine condition monitoring system is used. However, the work practically does not pay attention to vibration methods of engine condition diagnostics, which are important for diagnosing IFOs. Also, the types of damage are not sufficiently detailed.

In [13], an experimental study on the influence of IFOs on the technical condition of the gas turbine engine, namely the occurrence and appearance of cracks in the engine compressor blades, is reported. A model for predicting the growth of fatigue cracks in titanium alloy blades is proposed. It is established that the relationship between the impact force of FOs on the blades and the development of fatigue cracks. However, in [13], diagnostic indicators of crack development that could be used to design automated systems were not determined. It would be useful to define numerical threshold values for the width or depth of the crack.

In [14], the application of time-frequency analysis methods for diagnosing operational failures of aircraft engines was considered. The paper substantiated the advantages of this method, such as increased sensitivity to nonlinear changes in the signal and the possibility of detailed analysis of the vibration structure. However, in [14], a solution to the problem of interpreting the obtained results in cases with a strong noise background was not proposed.

In [15], the vibroacoustic signals emitted by the engine turbine during stationary excitation of vibrations were simulated for situations when all turbine blades are free of defects and one blade has a small fatigue crack. Bispectral analysis is used to process the diagnostic information. It is shown that the appearance and evolution of a fatigue crack in the blade changes the intensity of global and local extrema of bispectral modules.

At the same time, in [15], issues regarding the processing of the results of bispectral analysis remained unresolved, in particular, the establishment of a quantitative integrated indicator that would make it possible to automate the diagnostic process. Along with this, the use of a probabilistic neural network, which is proposed for recognizing the technical condition of blades, requires high computational complexity with a large amount of data.

In [16], an analysis of dynamic models of cracks in GTE blades, in particular "breathing" cracks, was conducted. Vibration characteristics that can be used to diagnose the technical condition of the engine were shown. However, in [16], such operational violations as IFOs were not considered. There are no recommendations for processing vibration signals to identify IFOs.

In [17], methods for analyzing nonlinear responses of a system with damage are considered, but they are not specified. The paper proposes combined statistical features that characterize nonlinearities and the use of neural networks for damage classification. However, the dynamic system given in [17], on the example of which this is considered, is not rotating, although it is oscillatory with various disturbances (very approximate). Another drawback of the work is that the sensitivity to early damage was not assessed.

Study [18] examines in detail the typical signs of damage to the blades of compressors of various types of gas turbine engines caused by impacts on various solid objects. However, the authors do not consider the change in engine parameters at the ingress of small-scale FOs.

In [19], a promising method for detecting IFOs and diagnosing the technical condition of GTE blades is proposed. The method is based on the analysis of statistical characteristics of vibration signals. Although the use of such methods has been shown to be effective, it is difficult to draw an unambiguous conclusion about the statistical reliability of the proposed approach due to the small sample of results. The disadvantage of the work is also that the studies were conducted under laboratory conditions and additional investigation is needed for its widespread implementation. Additional studies are also required for the interpretation of diagnostic images. The diagnostic method proposed in [19] can respond well to single impacts of FOs on the blades but be less sensitive to slow accumulating damage (for example, friction of FOs on engine blades). The gradation of changes in the diagnostic sign with the development of damage caused by IFOs is not covered.

In [20], numerical modeling methods and experimental studies are used to analyze the impact of IFOs. The study includes an analysis of the vibration characteristics of signals emitted systemically at IFOs. The shortcomings include the fact that the paper does not provide detailed information about the numerical methods and modeling parameters used, which makes it difficult to reproduce the results. Also, the work uses the influence of only a certain type of FOs for analysis, which also makes it difficult to establish a universal diagnostic sign of IFOs.

In [21], a study of the impact of FO impacts on the compressor blades of a gas turbine engine was conducted. An experimental testing method was presented, which includes measuring the vibrations of the blades when they collide with various objects. It was shown that the analysis of vibration characteristics makes it possible not only to detect the fact of the impact itself but also identify the characteristics of FOs that collided with the blade. The main achievement of [21] is the use of measurements of blade tip vibrations for accurate identification of the object and modeling the mechanism of its impact. However, the disadvantage is the orientation mainly on experimental tests without a thorough analysis of the application of early diagnostic methods under real operating conditions. In addition, the study does not pay sufficient attention to methods of automated processing of the received vibration signals, which is important for integration into aircraft engine condition monitoring systems.

One of the promising areas is the use of machine learning to detect various malfunctions of rotating systems. In [22], an approach to processing vibration signals using machine learning methods is reported. It is shown that classification algorithms can improve the accuracy of foreign object diagnostics. Along with this, the study has a number of comments, in particular, the complexity of training models and the need for a significant amount of data for their proper functioning.

In [23], the use of deep learning methods for detecting small FO ingress into GTE was proposed. To improve the diagnostics of IFOs and increase the accuracy of FO identification, the work used an approach that combines visual data analysis with the use of neural network algorithms. The advantage of the study is the use of artificial intelligence methods, which in the future would allow for the effective detection of FOs even of small sizes. The disadvantages of study [23] include the fact that the use of visual diagnostic methods has limited effectiveness when FO is outside the visibility zone of the cameras. In addition, the possibility of combining visual analysis with vibration signal processing methods, which could significantly increase the efficiency of diagnostics, is not considered.

Our review of the literature [9–23] demonstrates that although modern methods of processing vibroacoustic signals allow the detection of damage to gas turbine engines caused by FO ingress, most methods either do not provide sufficient sensitivity to small signal changes or require significant computing resources. The relationship between the change in the diagnostic feature and the degree of damage caused by the IFOs is not sufficiently revealed. There is also a problem with the interpretation of complex results of vibration signals, bispectral analysis, or statistical analysis in order to establish a quantitative integrated indicator of damage.

All this gives grounds to argue that it is advisable to conduct research aimed at improving the methods of vibroacoustic diagnostics of GTE, which would increase its sensitivity to small changes in diagnostic signals caused by the ingress of small foreign objects into the engine turbine.

3. The aim and objectives of the study

The aim of our research is to improve the efficiency of detecting small foreign objects in GTE by expanding the methods of vibroacoustic diagnostics through the use of multi-level signal processing. This will make it possible to determine a quantitative integrated indicator for the technical condition of the rotating system to detect damage caused by foreign objects before significant deformations of the rotating engine elements appear.

To achieve the goal, the following tasks were set:

– to conduct physical modeling of the rotating system and simulation of small foreign objects;

– to conduct multi-level processing of measured vibroacoustic signals and evaluate its effectiveness for identifying the impact of IFOs in the rotating system based on experimental data.

4. The study materials and methods

The object of our study is the process of monitoring the technical condition of an aircraft gas turbine engine. The subject of the study is methods of multi-level processing of vibroacoustic signals for diagnosing the ingress of foreign objects into the gas turbine engine and detecting operational disturbances.

The principal hypothesis of the study assumes that the use of multi-level processing of vibroacoustic signals could increase the sensitivity to small changes caused by the ingress of foreign objects into the gas turbine engine and provide more accurate identification of operational disturbances.

The assumptions accepted in the work are:

1. It is believed that the main source of changes in the characteristics of vibroacoustic signals is the IFOs in the turbine of the rotating system, even if they are small in size.

2. The ingress of foreign objects into the turbine of the gas turbine engine leads to changes in the structure of the vibroacoustic signal, which can be detected using multi-level processing.

3. It is assumed that the damage caused by FO ingress is not accompanied by a significant increase in the level of overall noise or signal energy in the early stages but causes a change in its structure.

4. The signals being analyzed may contain a significant level of noise; however, the use of multi-level processing methods makes it possible to identify the necessary diagnostic features.

The simplifications adopted in the work:

1. The design features of different types of GTE are not taken into account – the study is carried out on a generalized model of a rotating system.

2. Other sources of changes in vibroacoustic characteristics are not considered, except for the ingress of foreign objects (for example, bearing wear, unbalance, etc.).

3. All experimental measurements were carried out under the same conditions, with a constant rotation frequency, the same position of the sensors, a stable ambient temperature, and the same recording modes. This allows for correct comparison of signals in cases with and without damage.

4. It is assumed that the analysis of changes in the signal within a limited frequency range (0–10 kHz) is sufficient to identify the main diagnostic features associated with FO ingress.

Diagnostic information is represented in the form of low-frequency vibrations and acoustic noise in the range of 0–10 kHz [1]. Processing of such noise-like signals is complex, which complicates their interpretation, comparison, and isolation of diagnostic features. Therefore, most modern on-board vibration monitoring systems use diagnostic signal processing methods that allow for the approximate identification of defects and deviations in the operation of GTE. However, these methods only determine the engine states at which the parameters approach the permissible limits but do not provide for the detection of FO ingress, especially small ones, until the moment when damage to the rotating components of GTE becomes significant. To improve the efficiency of diagnostics of operational damage, it is necessary to expand the methods of vibroacoustic diagnostics capable of detecting the ingress of small FOs into the GTE turbine before significant deformations of its rotating elements occur.

The most informative for detecting changes caused by operational disturbances in the normal operation of the engine are the vibration velocity spectra at the rotor harmonics [1]. However, in the case of small FOs, such as sand or metal particles, entering the engine, the vibration or vibroacoustic signals usually do not undergo significant changes. This is explained by the fact that such objects do not cause an increase in the engine speed or significant mechanical deformations of its rotating components.

This can be explained by the fact that damage at the initial stage does not lead to a significant increase in the total level of radiated vibrations or acoustic noise or individual spectral components. However, the structure of the signal changes, that is, the ratios between its individual components change or new components appear [1].

When choosing diagnostic signal processing methods, the following requirements must be taken into account:

1) high sensitivity to small changes in useful information under conditions of significant additive and multiplicative noise;

2) the ability to identify local non-stationarity of the measured signal caused by the appearance and development of damage (or the ingress of small FOs into the engine turbine);

3) suitability for processing significantly non-stationary signals (at transient operating modes);

4) unambiguousness in interpreting the analysis results.

Methods that meet these requirements include the analysis of higher statistical and spectral characteristics [13], time-frequency transformations (spectrogram) [12], time-scale transformations (wavelet transform), and fractal analysis [24, 25]. Such methods are often combined to solve specific problems of multi-class diagnostics [9, 10].

Methods of time-frequency analysis and spectral analysis of higher orders (bispectral analysis) are used to process vibroacoustic signals for the purpose of early detection of damage to rotating components of GTE [1]. Time-frequency analysis of signals makes it possible to determine how spectral components change over time [12].

Bispectral analysis is a higher-order method for analyzing nonlinearities and phase relationships in a signal, which makes it possible to detect hidden patterns that may be inaccessible to conventional spectral methods [13]. The effectiveness of higher-order characteristics is explained by their ability to suppress noise components, in particular Gaussian ones, in measured signals, identify statistically related segments of the spectrum, and detect combined or modulation frequencies.

Wavelet transform is an effective method for analyzing non-stationary processes, and wavelet filtering is used for pre-processing complex signals [1].

The application of fractal analysis methods to the results of time-frequency or bispectral analyses makes it possible to obtain a quantitative integrated assessment of signal fragments, which can be used as a diagnostic feature for determining the technical condition of the engine [10]. The combination of these methods or their sequential application for processing vibroacoustic signals under both stationary and non-stationary modes of operation of the gas turbine engine expands the functional capabilities of diagnostic methods for detecting the ingress of small FOs and identifying operational violations [26].

To improve the efficiency of detecting damage caused by the ingress of small FOs, multi-level processing was applied to the measured vibroacoustic signals, which implemented a comprehensive approach to analyzing changes in the technical condition of RS. The processing consisted of three main stages:

– first stage: time-frequency analysis (construction of spectrograms);

– second stage: bispectral analysis;

– third stage: fractal analysis of images – bispectral estimation modules.

The first stage included time-frequency analysis, the result of which are three-dimensional plots – spectrograms for full-length signals (covering the entire operating cycle of the rotating system). The Hamming function was used as a window function. This stage solved the problem of localizing a potential defect in time and forming target signal fragments for in-depth analysis.

At the second stage, bispectral analysis was applied to the selected signal fragments and bispectral spectra were obtained, represented in the form of full-color contour images. The use of bispectral analysis made it possible to detect nonlinear relationships between the frequency components of the signal, invisible during standard spectral analysis. Bispectral images were obtained for different technical states of RS: standard operation mode without external influences; during small FO ingress and during blade friction as a result of IFOs. The resulting diagnostic images demonstrated the presence of differences in energy distribution, but these differences were difficult to classify. Thus, the second stage implemented the task of constructing an integrated diagnostic image of the system state.

At the third stage, fractal analysis was applied. In order to quantitatively assess the changes caused by damage, the Boxcount algorithm was used to calculate the Minkowski fractal dimensionality (D_M) [9, 10]. That made it possible to move from visual analysis to quantitative interpretation of the complexity of the signal structure.

The interpretation of the Minkowski dimensionality is related to the complexity and density of the analyzed image. The value of D_M approaches 2 in the cases of higher image density, indicating its more complex and irregular structure, while it tends to 1 in the cases of lower image density, reflecting a more uniform and less confusing pattern [12, 25].

To conduct the study, a physical simulation of the rotating system was performed, vibroacoustic signals were measured, and the measured signals were processed using the proposed multilevel processing methods. The vibroacoustic signals measured during the study were processed in the MATLAB program. The HOSA (Higher-Order Spectral Analysis) function library was used to calculate and graphically visualize the estimates of the bispectrum magnitude.

5. Results of vibroacoustic signal processing for diagnosing rotating system disturbances caused by foreign objects

5. 1. Physical modeling of the rotating system and simulation of small foreign objects

Physical modeling of vibroacoustic processes during IFOs in a rotating system (RS) was carried out by experimental studies of vibroacoustic signals emitted by the physical model of RS under both stationary and non-stationary oscillatory disturbances [26].

An air starter (supercharger) was used as a physical model of RS to start an aircraft engine, which has 14 blades made of titanium alloy (Fig. 1). The air supercharger was driven by a DC motor with a regulated speed and a power of 1 kW, with a maximum speed of up to 6000 rpm.

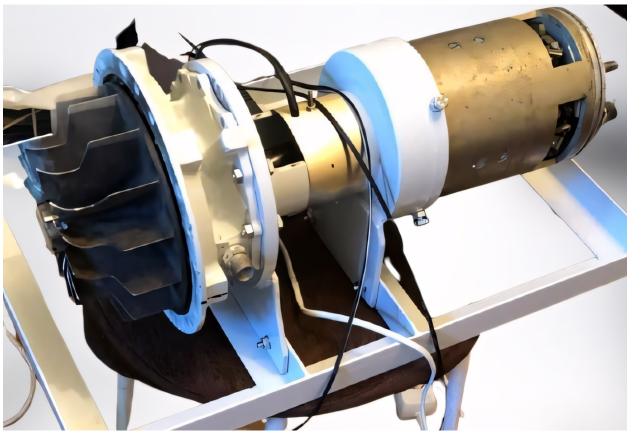

Fig. 1. General view of the physical model of a rotating system

The measuring system used for the study consisted of the following components:

– dynamic microphone (Soundking EH002 series) with an amplifier that provides a linear response in the frequency range from 10 Hz to 50 kHz;

– tachometer;

– dual-channel digital oscilloscope ISD205A;

– personal computer with appropriate software.

The first channel of the oscilloscope was fed with a signal from the microphone amplifier, and the second channel was fed with a signal from the tachometer.

Experimental studies were conducted at a turbine speed of 3000 rpm under a stationary mode. The implementations of vibroacoustic signals were obtained with a sampling frequency of 16 kHz. The drive mechanism is switched on and off in such a way that during the observation time interval the acceleration modes, stationary operation with a constant speed and coasting mode are simulated. A sample of the measured vibroacoustic signals is shown in Fig. 2.

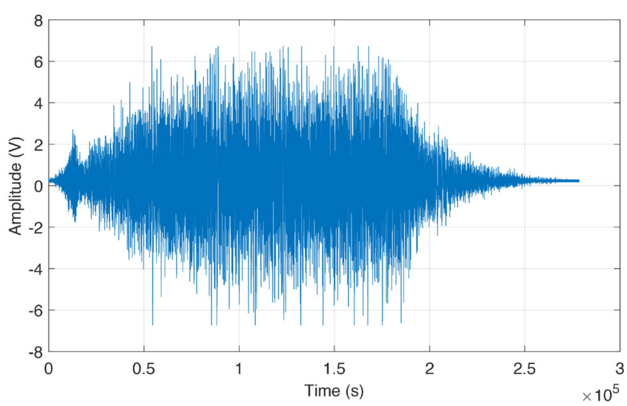

Fig. 2. Example of a vibroacoustic signal generated by a physical model of a rotating system

At the next stage of the study, a simulation of FO ingress into the engine turbine and blade friction as a result of IFOs was carried out.

To simulate the ingress of small FOs in the turbine compressor, 31 aluminum foil balls were used. The mass of each ball was approximately mi=0.17±10 % g, diameter di=0.009–0.01 m.

According to the devised methodology, experimental studies were conducted both under normal operating conditions (without external influence) of the system and with the introduction of two groups of small balls during stationary engine operation. In the first experiment, 17 balls with a total mass of 3 g were introduced into the turbine compressor, and in the second, 14 balls with a total mass of 2.5 g.

For simulation modeling of turbine blade friction due to IFOs, a suitable procedure was devised. At the first stage, the reference signal was measured (without disturbances under the operating modes of RS). The blade friction was simulated using a rectangular sheet of cardboard (300×170 mm), which was slightly pressed against the turbine blades during RS operation. In the first experiment, the blade friction was simulated during the entire system operation cycle, and in the second – only during the stationary mode of the rotating system.

5. 2. Multilevel processing of vibroacoustic signals measured during physical modeling

Fig. 3 shows the results of time-frequency analysis in the form of three-dimensional plots. Analyzing the obtained spectrograms, the time interval corresponding to the impact of the balls into RS turbine was determined, and a fragment of the signal containing the moment of impact of the balls was selected for further processing. In the case of blade friction, as a result of IFOs, signal fragments covering the friction process were also selected for processing. All selected signal fragments were of the same length (30,000 samples).

As shown in Fig. 3, *a*, *b*, the impact of small balls caused an increase in the intensity of the signal components in the measured vibroacoustic signal, especially in the high-frequency range (f>2 kHz), precisely during the time interval of the experiment when the balls were thrown (time interval: 9–10 s). The level of intensity of the signal components depends on the direction and force of the balls hitting the blades.

The results of the time-frequency analysis of the vibration signals measured during the friction of the turbine blades of the RS are shown in Fig. 3, *c*, *d*. As can be seen, the signals have a higher noise level compared to those measured during the simulation of the ingress of small FOs. The structure of the signal measured during the friction of the turbine blades under the stationary mode of operation of RS (time interval 7–8 s) contains increased vibration levels. However, during acceleration, transient mode, and advance, the vibration level does not increase.

At the second level of processing, bispectral analysis was applied to the selected signal fragments, which represent the operation of the system before and during the impact of the balls, as well as before and during the friction of the turbine blades. Accordingly, the bispectral values were determined. Examples of the results of bispectral analysis of the measured vibroacoustic signals are shown in Fig. 4.

From the results of bispectral analysis it is clear that the estimates of the bispectral modulus for selected fragments of vibroacoustic signals differ. However, on the basis of such images it is difficult to distinguish a diagnostic feature sufficient for classifying the state of the rotating system and identifying the IFOs.

Therefore, for the obtained images it was proposed to determine the Minkowski fractal dimensionality D_M using the Boxcount algorithm [26]. The calculation of the Minkowski dimensionality makes it possible to obtain a quantitative integrated measure for the geometry of the isolines.

As a result of multilevel processing of the measured vibroacoustic signals, the average values of Minkowski dimensionality for the estimates of the bispectral modulus were obtained. The results are given in Table 1.

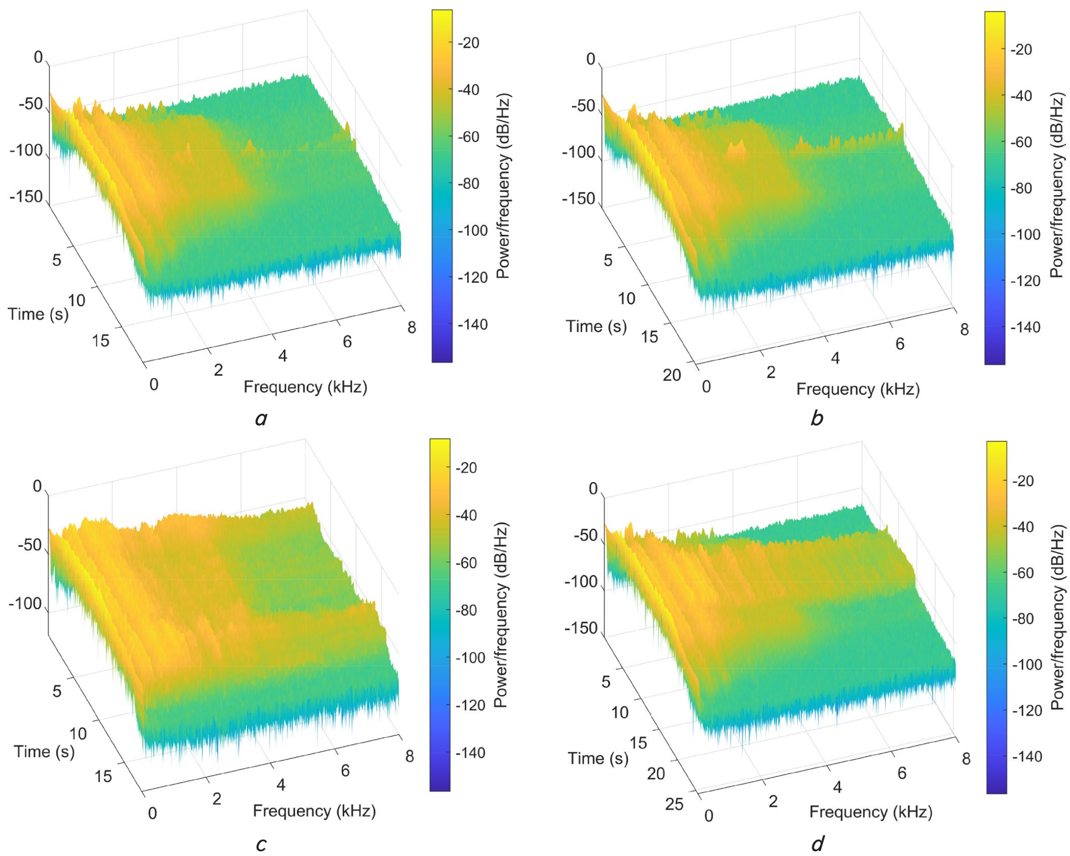

Fig. 3. Results of time-frequency analysis of vibroacoustic signals: *a* – ingress of the first batch of balls (17 pcs); *b* – ingress of the second batch of balls (14 pcs); *c* – friction of turbine blades during the entire operating cycle; *d* – friction of turbine blades only under the stationary operation mode of the rotating system

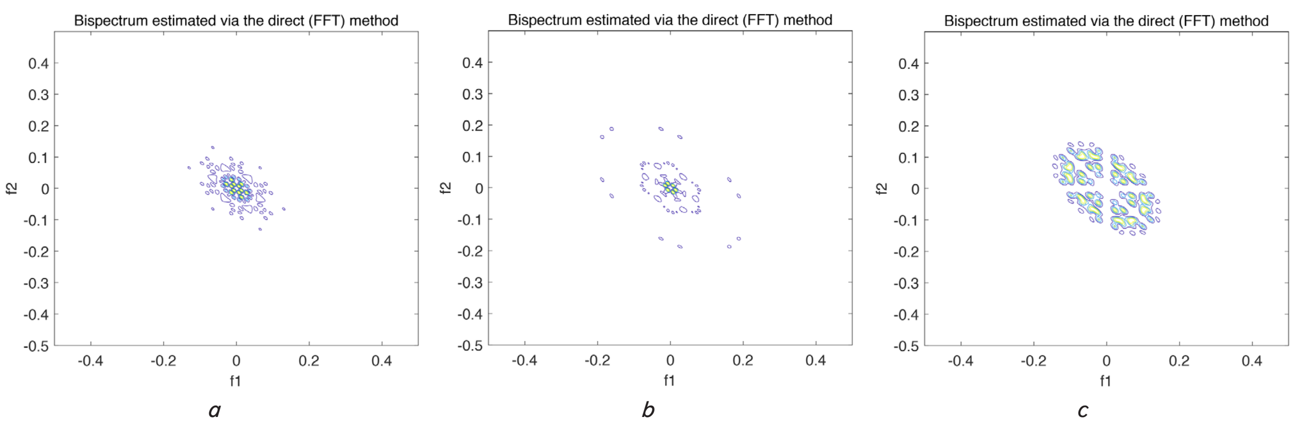

Fig. 4. Results of bispectral analysis of vibroacoustic signal fragments measured under the stationary mode of operation of the rotating system: *a* – without operational disturbances; *b* – during the ingress of small foreign objects; *c* – during friction of the blade against a foreign object

Table 1

Average values of Minkowski dimensionality for estimates of the bispectrum modulus

Technical condition of the rotating system	Minkowski dimensionality, D_M
No external influence (normal operation of the rotating system)	1.075
Ingress of small foreign objects	1.01
Friction of blades against a foreign object as a result of its entry into the rotating system turbine	1.21

As can be seen from our results, there is a clear change in the Minkowski dimensionality: its value increases as the damage progresses. This indicates that an increase in the D_M value can serve as an indicator of the development of a defect caused by the ingress of small foreign objects. Thus, the Minkowski dimensionality is an effective diagnostic indicator for detecting operational violations and monitoring the technical condition of the gas turbine engine.

6. Discussion of results based on the multi-level processing for the diagnosis of rotating system disturbances caused by foreign objects

The result of our study is the physical modeling of RS, the general view of which is shown in Fig. 1. In addition, simulation modeling of a small-sized IFOs and blade friction as a result of IFOs was carried out. Measured vibroacoustic signals were used for multi-level processing (an example of measured signals is shown in Fig. 2).

The results of time-frequency analysis, shown in Fig. 3, demonstrated that the ingress of a small-sized FOs causes an increase in the intensity of components in the measured vibroacoustic signal. Thus, a potential defect was localized in time and target signal fragments were formed for further processing.

An integrated diagnostic representation of the system state was obtained at the second level of multi-level processing from the results of bispectral analysis shown in Fig. 4. The results demonstrated a change in the technical condition of RS. However, based on such representations, it is difficult to distinguish a diagnostic feature sufficient for categorizing the state of RS and identifying the IFOs. Therefore, it was proposed to determine the Minkowski fractal dimensionality D_M for the obtained representations.

Thus, as a result of multi-level processing of vibroacoustic signals, a quantitative integrated indicator was established – Minkowski dimensionality; the average values for operation of the system without external influence and with the development of damage caused by IFOs are given in Table 1.

The features of our results, which make it possible to improve the methods of vibroacoustic diagnostics of GTE, are explained by the establishment of an integrated-numerical indicator (Minkowski dimensionality). A tendency was revealed for the value of the Minkowski dimensionality of estimates of the bispectrum modules to increase with the increase in operational damage caused by IFOs of a small size (Table 1).

That is, the use of Minkowski fractal dimensionality as an integrated quantitative indicator makes it possible to assess the nature of processes occurring in the engine and identify trends that may lead to failure. The application of fractal analysis makes it possible, using small hardware computing capabilities, to increase the sensitivity of vibration diagnostics to small changes in signals caused by the ingress of small-sized FOs.

Our results are consistent with the previous findings reported in [9, 10]: the emergence of damage creates additional nonlinearities in vibration signals and forms the emergence of a certain trend, which is so well revealed by fractal analysis methods.

Unlike study [15], in which the use of time-frequency analysis is limited by difficulties of interpretation in the cases with a strong noise background, the proposed approach provides an unambiguous change in the indicator, which increases its informativeness. One of the advantages of our study is also low computational requirements for the algorithm for calculating Minkowski dimensionality, which makes it suitable for use in automated systems for monitoring the technical condition of GTE.

Practical application of these research data will make it possible to automate the process of diagnosing vibration or vibroacoustic signals for early detection of damage to GTE and its rotating components caused by IFOs in the engine turbine. Also, the devised diagnostic methodologies could be programmatically adapted to existing on-board control systems, which are currently used for AI-450 engines [26].

The limitations in this study relate to the problem of reproducibility of the results. There is a need to improve the methodology to ensure its reproducibility on different types of engines and under different operating conditions. Only then can it be confidently stated that the results could be reproduced in other settings. Currently, the methodology can be adapted only for specific types of engines, which limits its applicability in a wide range of real operating conditions.

One of the important limitations of the study is that Minkowski dimensionality would increase in the case of the emergence and development of an RS imbalance. In turn, IFOs can cause the emergence of an imbalance. Therefore, it is necessary to expand the classes of diagnosed operational disturbances of GTE, especially under non-stationary operating modes.

The main drawback of our study is that the analysis of Minkowski fractal dimensionality was carried out only on a limited sample of vibroacoustic signals emitted by RS. Although the measurement was carried out a sufficient number of times, taking into account the various design features of different types of engines, it is necessary to expand the research sample. Also, the disadvantages include the fact that other parameters of RS operation (temperature, pressure, etc.) were not taken into account during physical modeling. The study does not cover the calculation of the adaptive threshold value of Minkowski dimensionality for different types of GTE.

Future research may focus on expanding the diagnostic dataset to confirm the statistical reliability of multi-level processing for steady-state and non-steady-state operating conditions of GTE. A large diagnostic dataset is also needed to establish the physical parameters of FOs and its potential damage to GTE.

Continuation of our studies may involve designing an automated system by using deep learning and implementing artificial intelligence methods to improve the efficiency of early identification of IFOs in the GTE turbine.

7. Conclusions

1. Physical modeling of the rotating system and simulation of various operational disturbances caused by the influence of foreign objects on its operation have been carried out. The simulation included the impact of 31 aluminum foil balls and modeling of blade friction using a cardboard sheet. A measuring system was used to record the signals, which included a dynamic microphone, a tachometer, a two-channel digital oscilloscope, and a personal computer with appropriate software. Vibroacoustic signals were obtained at a sampling frequency of 16 kHz.

2. Multilevel processing of vibroacoustic signals has been proposed and substantiated, which includes a combination of frequency-time analysis, higher-order spectral analysis (bispectral analysis), and fractal analysis. Multilevel processing of measured signals makes it possible to obtain a quantitative integrated estimate – Minkowski dimensionality for estimates of the bispectral modulus – and can be used to identify small-sized IFOs in the engine turbine and make decisions on the technical condition of the gas turbine. It was established that Minkowski dimensionality is a valuable diagnostic feature for detecting operational disturbances in the engine, as a result of the ingress of especially small-sized FOs. The D_M value for the system operation without operational disturbances was 1.075, when small foreign objects hit it – 1.01, and when the blades rub against a foreign object – 1.21. Thus, a clear trend has been

demonstrated: an increase in Minkowski dimensionality with the development of a disturbance in the rotating system due to IFOs. The proposed approach could be used in on-board monitoring systems to detect anomalies in the operation of GTE, which may indicate the ingress of foreign objects into the engine.

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, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Bouraou, N. (2023). Methodology of Vibroacoustic Monitoring and Diagnosis of Initial Damage of Elements of Rotating Systems. Advanced System Development Technologies I, 311–344. https://doi.org/10.1007/978-3-031-44347-3_9
2. Rossmann, A. (2015). Aircraft turbine engine safety volume 4B: Problem. Oriented technology for professionals. Axel Rossmann Turboconsult, 434.
3. Sharma, R., Singh, S., Singh, A. K. (2018). Foreign Object Damage Investigation of a Bypass Vane of an Aero-engine. Materials Today: Proceedings, 5 (9), 17717–17724. https://doi.org/10.1016/j.matpr.2018.06.094
4. Strack, W., Zhang, D., Turso, J., Pavlik, W., Lopez, I. (2005). Foreign object damage identification in turbine engines. NASA/TM-2005-213588. Available at: https://www.researchgate.net/publication/24330663
5. Madhavan, S., Jain, R., Sujatha, C., Sekhar, A. S. (2014). Vibration based damage detection of rotor blades in a gas turbine engine. Engineering Failure Analysis, 46, 26–39. https://doi.org/10.1016/j.engfailanal.2014.07.021
6. Tsai, G.-C. (2004). Rotating vibration behavior of the turbine blades with different groups of blades. Journal of Sound and Vibration, 271 (3-5), 547–575. https://doi.org/10.1016/s0022-460x(03)00280-3
7. Kriston, B. J., Jálics, K. (2021). Application of vibro-acoustic methods in failure diagnostics. Journal of Physics: Conference Series, 1935 (1), 012002. https://doi.org/10.1088/1742-6596/1935/1/012002
8. Doshi, S., Katoch, A., Suresh, A., Razak, F. A., Datta, S., Madhavan, S. et al. (2021). A Review on Vibrations in Various Turbomachines such as Fans, Compressors, Turbines and Pumps. Journal of Vibration Engineering & Technologies, 9 (7), 1557–1575. https://doi.org/10.1007/s42417-021-00313-x
9. Pazdrii, O., Bouraou, N. (2020). Vibroacoustic condition monitoring of the complex rotation system based on multilevel signal processing. Vibrations in Physical Systems, 31 (2). https://doi.org/10.21008/j.0860-6897.2020.2.24
10. Bouraou, N. I., Ignatovich, S. R., Pazdrii, O. Ya. (2018). Using fractal analysis of the time-frequency spectra of vibroacoustical signals for diagnostic of gas-turbine engines. Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia, 74, 73–83. https://doi.org/10.20535/radap.2018.74.73-83
11. Mishra, R. K., Srivastav, D. K., Srinivasan, K., Nandi, V., Bhat, R. R. (2014). Impact of Foreign Object Damage on an Aero Gas Turbine Engine. Journal of Failure Analysis and Prevention, 15 (1), 25–32. https://doi.org/10.1007/s11668-014-9914-3
12. Turso, J. A., Litt, J. S. (2005). A Foreign Object Damage Event Detector Data Fusion System for Turbofan Engines. Journal of Aerospace Computing, Information, and Communication, 2 (7), 291–308. https://doi.org/10.2514/1.12348
13. Yang, S., Du, T., Zhang, X., Ma, L., Zhang, G. (2023). Effect of foreign object damage on vibration fatigue crack propagation of blades. Binggong Xuebao/Acta Armamentarii, 44 (6), 1713–1721. https://doi.org/10.12382/bgxb.2022.0109
14. Sopilka, Yu. V. (2005). Vykorystannia chastotnochasovykh peretvoren Vihnera vyshchykh poriadkiv u zadachakh vibroakustychnoi diahnostyky. Naukovi visti NTUU «KPI», 6, 110–117.
15. Bouraou, N. I., Protasov, A. G., Sopilka, Y. V., Zazhitsky, O. V. (2005). Decision making of aircraft engine blades condition based on bispectral analysis of the vibroacoustical signal. AIP Conference Proceedings, 760 (1), 760–766. https://doi.org/10.1063/1.1916751
16. Ma, H., Wu, Z., Zeng, J., Wang, W., Wang, H., Guan, H., Zhang, W. (2023). Review on Dynamic Modeling and Vibration Characteristics of Rotating Cracked Blades. Journal of Dynamics, Monitoring and Diagnostics. https://doi.org/10.37965/jdmd.2023.465
17. Samadani, M., Kitio Kwuimy, C. A., Nataraj, C. (2015). Model-based fault diagnostics of nonlinear systems using the features of the phase space response. Communications in Nonlinear Science and Numerical Simulation, 20 (2), 583–593. https://doi.org/10.1016/j.cnsns.2014.06.010
18. Ma, C., Wang, Y.-N., Wu, Y.-G., Xu, J.-X. (2017). Hard object impact damage characteristics of aero engine fan blade. Hangkong Dongli Xuebao/Journal of Aerospace Power, 32 (5), 1105–1111. https://doi.org/10.13224/j.cnki.jasp.2017.05.011
19. Zhang, Z. H., Li, J. W., Mei, K., Wang, J., Wang, N. F. (2020). Foreign Object Impact Detection of Aero-Engine Fan Based on Statistical Characteristics. Tuijin Jishu/Journal of Propulsion Technology, 41 (10), 2325–2331. https://doi.org/10.13675/j.cnki.tjjs.190401

20. Zhang, S., Dong, J. (2024). Numerical simulation and experimental analysis of foreign object impact on aero-engine fan rotor blade. Journal of Physics: Conference Series, 2762 (1), 012038. https://doi.org/10.1088/1742-6596/2762/1/012038
21. Yang, X., Lei, X. (2020). Foreign Object Impact Detection and Identification Test of Fan Blade. 2020 11th International Conference on Prognostics and System Health Management (PHM-2020 Jinan), 575–580. https://doi.org/10.1109/phm-jinan48558.2020.00112
22. Ogaili, A. A. F., Jaber, A. A., Hamzah, M. N. (2023). A methodological approach for detecting multiple faults in wind turbine blades based on vibration signals and machine learning. Curved and Layered Structures, 10 (1). https://doi.org/10.1515/cls-2022-0214
23. Mo, Y., Wang, L., Hong, W., Chu, C., Li, P., Xia, H. (2024). Small-Scale Foreign Object Debris Detection Using Deep Learning and Dual Light Modes. Applied Sciences, 14 (5), 2162. https://doi.org/10.3390/app14052162
24. Zmeskal, O., Dzik, P., Vesely, M. (2013). Entropy of fractal systems. Computers & Mathematics with Applications, 66 (2), 135–146. https://doi.org/10.1016/j.camwa.2013.01.017
25. Moreno-Gomez, A., Machorro-Lopez, J. M., Amezquita-Sanchez, J. P., Perez-Ramirez, C. A., Valtierra-Rodriguez, M., Dominguez-Gonzalez, A. (2020). Fractal dimension analysis for assessing the health condition of a truss structure using vibration signals. Fractals, 28 (07), 2050127. https://doi.org/10.1142/s0218348x20501273
26. Pazdriy, O. Ya. (2024). Vdoskonalennia bortovoi systemy keruvannia i kontroliu dlia bahatoklasovoi diahnostyky aviatsiynoho hazoturbinnoho dvyhuna. Kyiv, 236. Available at: https://ela.kpi.ua/items/23e11037-1a0a-45d4-a79b-97b17efd5f81