Wavelet Decomposition for Diagnosing the Technical State of the Engine Automatic Control Systems

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The paper describes the features of building efficient and reliable ACS aircraft power plant within the identifying dynamic characteristics, which allows, on the one hand, to organize optimal control with adaptation to changing external conditions and, on the other hand, to take timely and correct decisions when violations occur in the power plant or in the control part of the ACS. By using this approach, the problem arises of defining the identification methods that allow, in addition to assessing the current state of the system, to carry out a reliable and timely diagnosis of possible violations. It is proposed to use the coefficients of the wavelet decomposition of the characteristics of a closed ACS as identified parameters, which will help to avoid the problem of ensuring the fault stability of the system. In order to increase the reliability of the electronic systems of automatic control, the use of automatic control systems and diagnostics of their state is considered for the purpose of making control decisions in case of malfunctions of the engine or control system. The control of typical failures at the early stage of designing engine ACS allows the use of control system as a coordinator, modifying the control algorithm in critical situations while maintaining the acceptable level of quality. Therefore, further improvement of the methods of constructing high-efficiency ACS is the study of reviewed models of recognition and visualization of the system operation with the definition of energy-active points based on the multifractal formalism for the description of dynamic systems. On the basis of the algorithm of the wavelet coefficient decomposition (mathematical description of the system), a technical implementation (structural scheme of the automatic control system) for the development of nano- and microelectronic devices of the engine control system with properties of the confidence coefficients on the distribution scale is proposed.

Keywords: Wavelet, Electronic control system, Dynamic characteristics, Identification, Fault stability, Multifractal formalism.

1. INTRODUCTION

The development of gas turbine engines (GTE) of complex circuits with regulated elements of the flowing part (the compressor distributor, nozzle), with an afterburner combustion chamber, with an adjustable propeller, an increase in the parameters of the working process (temperature and pressure of the gas) led to the complication of control problems caused by the interaction of control circuits, the appearance of the fields of joint operation of the regulators. Possibilities for solving the causative problems were related to the development of methods for reducing the influence of the interaction of control channels, in particular, the construction of autonomous automatic control systems (ACS), the application and development of the invariance theory, taking into account the features of the GTE control.

Further development of the scope of tasks solved in flight, increasing requirements to engines by the level of the main characteristics (specific parameters, reliability, resource) required more accurate accounting of changing operating conditions in the flight, improving the accuracy of control on the established and transitional modes of operation to ensure the possibility of realizing the characteristics of the engine installed during its design and increase the efficiency of the aircraft.

The solution to these tasks was made possible by the development of adaptive and integrated control of the power plant, which allows the automatic control equipment to obtain the characteristics of the engine and power plant in general, the best for the specific conditions of the flight, for example, the best efficiency of the engine on a cruise flight, high fidelity of the fighter plane; necessary reserves of gas-dynamic stability under the influence of strong perturbations (external and internal) and during flight at high altitudes.

In order to achieve the optimal operation of the control system with the use of adaptive and integrated approach, it is necessary to take into account the suitability control property – the definition of monitoring tools, software control systems (wavelet-neural network, genetic algorithms) and the introduction of nets information technology.

A great contribution to the development of suitability control property of aviation gas turbine engines and their control systems has been made by the scientists of the Central Institute of Aviation Motors: Birger I., Dubravsky N., Karasev V., Stepanov V. [1] and Hispano-Swiza, BAE Systems Enterprises, FADEC International LLC [2-4].

The aim of this research is to define the optimal methods and control rules that should allow to solve the problems of diagnostics and design of automatic control system of GTE, providing the correct operation mode of the engine based on impulse transient functions.

2. POWER STATE DIAGNOSING TECHNIQUE FOR AUTOMATIC CONTROL SYSTEM AVIATION ENGINE

2.1 System Feature Recognition

The choice of optimal decision rules is determined primarily by the available a priori and a posteriori information [5]. Available a posteriori information will be

considered only identifiable coefficients of the decomposition of the impulse transient functions in a row of wavelet functions $\{c_j\}$. In real ACS power plant of the aircraft, of course, other information is also available, depending on the specific system, but the analysis of specific systems is beyond the aim of this work. The a priori information necessary in any case is the alphabet of situations $\{D_i\}$. Below there are three options for recognizing possible situations in the system, depending on the amount of a priori information:

1) only the directions of changes in the values of the decomposition coefficients of the impulse transient function (ITF) during the transition from normal to critical situations are known;

2) the values of the decomposition coefficients $\{c_j^i\}$ in all situations $\{D_i\}$ are known;

3) there is sufficient statistical information: a priori probabilities of situations $P(D_i)$, conditional probability density values of signs $f(c_j / D_i)$, and these distributions are unimodal, as well as the required probabilities P_i^* of detection of the situations D.

In the first case, when obtaining of the reliable a priori information is difficult, and the cost of calculating the decomposition coefficients c_j is low (or they are used for other purposes), it is possible to use a very simple diagnostic procedure based on the analysis of the sign of deviation of the monitored parameter from the nominal value. At the same time, in order to improve the reliability of diagnostics, it is advisable to allocate intervals $\left(c_j^0 - \varepsilon_j, c_j^0 + \varepsilon_j\right)$ for each decomposition coefficient c_j with a nominal value c_j^0 and an error of determination ε_j.

Let the code case $c_j \in \left(c_j^0 - \varepsilon_j, c_j^0 + \varepsilon_j\right)$ of the value 0, cases of $c_j < c_j^0 - \varepsilon_j$ of the value −1 and cases of $c_j < c_j^0 + \varepsilon_j$ of the value +1.

As a rule, a full set of coefficients is redundant. A convenient method of minimizing the number of controllable parameters is the method proposed by Sindeyev I. [6]. It allows to determine the most informative parameters using the situation table and shows the way of creating a logical device for detecting situations. The method is also operable for the three-valued logic used in this case. Having minimized the set of monitored decomposition coefficients, it is possible to obtain a very simple logical algorithm for diagnosing, which can be easily implemented both in the on-board computer (OnCPU) and hardware.

In the case when the values of the decomposition coefficients are known in all situations, each state of the system being diagnosed can be represented as (n+1)-dimensional vector C with components $\{c_{j0}, c_{j1}, \ldots, c_{jn}\}$.

The task of classifying situations $\{D_i\}$ in this case may be formulated as follows: the required set of parameters (decomposition coefficients) is required to be assigned to one of the predetermined diagnoses (situations). Diagnosis is carried out by the distance of the current vector C to the sets C_{D_i}. (or by the distance to the standard, the coordinates of which are equal to the average values of the coordinates included in this set).

The recognition procedure is simplified, when encoding features in a binary code: 1 is the presence of a feature, 0 is the absence of a feature. The belonging of the diagnosed system to a certain situation $D_j \in D_i (i = 0,1,\ldots,L)$ is determined by the condition [6, 7]

$$\frac{1}{v_j} \sum_{s_j=1}^{v_j} \left[R_{n+1}\left(C, C_{D_j}^{s_j}\right)\right] = \max \frac{1}{v_i} \sum_{s_i=1}^{v_i} \left[R_{n+1}\left(C, C_{D_i}^{s_i}\right)\right]$$

$$R_{n+1}\left(C, C_{D_j}^{s_j}\right) \geq E, \quad R_{n+1}\left(C, C_{D_j}^{s_i}\right) \geq E, \quad i = 0,1,\ldots, L, \tag{1}$$

where C is the current state vector of the system being diagnosed; $C_{D_j}^{s_j}$ are the coordinates of points corresponding pluralities; ($s_j = 1,2,\ldots,v_j$ are the numbers of points belonging to the plurality D_j); R_{n+1} are the metrics in the space $\{D_i\}$; E are the recognition thresholds.

In this case, R_{n+1} represent the number of zero coordinates (n+1) – the coordinate matching vectors formed by adding modulo 2 vectors C to the vectors (n+1), the number of binary coordinates that match one another.

The process of diagnosing is coming to coordinate-wise addition modulo 2 of the vector, corresponding to the recognizable state of the system, with each of the vectors of all situations from zero to L. In the mapping vectors thus obtained, the number of zero coordinates is calculated and those of them are selected for which this number is greater than a certain threshold value E. The calculated mean values of the zero coordinates for each of the classes are compared with each other. The state of the system being diagnosed corresponds to the situation for which the mean value of the zero coordinates is the highest.

Obviously, in this case it is also unreasonable to calculate and compare (n+1) coefficients c_j and it is necessary to choose the most informative coefficients, allowing to reliably recognize individual situations. As a criterion for the informativity of the coefficient c_j^M in a situation M, one can use the minimum (in absolute value) difference between the value of this coefficient in the situation under consideration and its values in other situations:

$$S_j^M = \min_{\substack{i=0,\ldots,L \\ i \neq M}} / c_j^M - c_j^i /, \tag{2}$$

where L is the number of critical situations; $i = 0$ corresponds to the normal situation.

The larger value of the criterion S_j^M, the more informative the coefficient c_j in the situation of M. But to

compare the values of the criteria in different situations and with different numbers, relative estimations of the informativity criteria are necessary. It is possible to take the ratio of S_j^M to the rms value of the coefficients c_j with the number j in possible situations or take the value of S_j^M to the rms value of the coefficients c_j^M in the situation M. Accordingly, two relative informativity criteria are obtained:

$$q_j^M = \frac{S_j^M}{\sqrt{\frac{1}{L+1}\sum_{i=0}^{L}\left(c_j^i\right)^2}};$$ (3)

$$g_j^M = \frac{S_j^M}{\sqrt{\frac{1}{n+1}\sum_{j=0}^{n}\left(c_j^M\right)^2}}.$$ (4)

2.2 Decomposition Coefficient Algorithm

Let us consider the structure of the two-dimensional ACS GTE shown in Fig. 1. For its diagnosing it is advisable to use statistical recognition methods, for example, the minimum risk statistical method [6].

This is due to the fact that for the expansion coefficients in different situations in the general case the separation hypothesis due to errors caused by interference may not be observed. But the direct application of
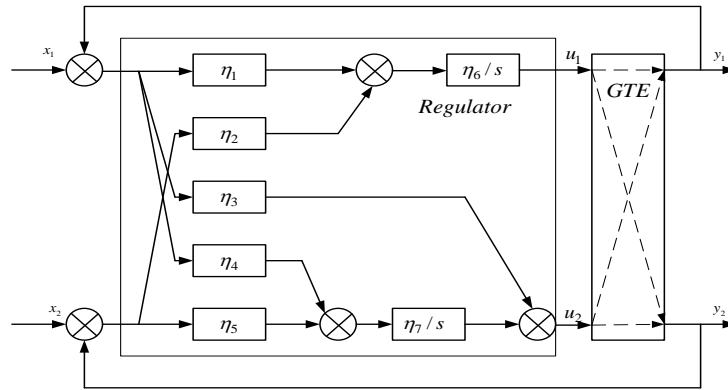

Fig. 1 – The structure of the two-dimensional ACS GTE

the minimum risk method [7] in the problem is inefficient due to large computational costs, which is unacceptable for onboard CPU. Obviously, an effective diagnostic procedure should control the minimum number of decomposition coefficients using a small number of simple computational operations, for example, by hitting the current values of the coefficients at predetermined intervals.

The following algorithm can be proposed for selecting the most informative diagnostic features.

1. For each considered situation D_i for the coefficients are searched for the boundary values α_j^i and β_j^i $\left(j=0,\ldots,n,\ \alpha_j^i<\beta_j^i\right)$ are such that when $c_j\in\left(\alpha_j^i,\beta_j^i\right)$ the risk of making a decision about the situation is minimal. The minimum risk criteria are transformed into the maximum criteria of a posteriori information with the accepted form of the payment matrix C [6, 7], according to which the boundary values α_j^i and β_j^i are determined as the limits of inequality

$$k = \min_{\substack{0,\ldots,L \\ k\neq i}} \frac{f\left(c_j/D_i\right)}{f\left(c_j/D_k\right)} > \frac{P\left(D_k\right)}{P\left(D_i\right)}.$$ (5)

The block diagram of the numerical algorithm for finding the quantities α_j^i and β_j^i under the condition of the single-mode distribution of the $f(c_j/D_i)$ is shown in reference [8].f

2. For each pair α_j^i, β_j^i the probability is calculated as

$$P_j^i = P\left(\alpha_j^i < c_j < \beta_j^i / D_i\right) = \int_{\alpha_j^i}^{\beta_j^i} f\left(c_j / D_i\right)dc_j.$$ (6)

At $P_j^i > P_i^*$, the found diagnostic feature $c_j\in\left(\alpha_j^i,\beta_j^i\right)$ makes it possible to detect situation D_i with a given probability.

3. If for the situation D_k it was not possible to find a single pair α_j^k and β_j^k, satisfying the condition $P_k > P_k^*$, then the situation D_k can be tried to be controlled by several decomposition coefficients of c_j, for example, by three coefficients c_{j1}, c_{j2}, c_{j3}; with the highest values of P_j^i, making a decision on the majority principle. In this case, the probability of finding a situation D_k is

$$P_k = 3\left(P_{j1}^k + P_{j2}^k + P_{j3}^k - 1\right) - 2(P_{j1}^k P_{j2}^k + P_{j1}^k + P_{j3}^k + P_{j2}^k P_{j3}^k) + P_{j1}^k P_{j2}^k P_{j3}^k$$ (7)

where $P_{j1}^k, P_{j2}^k, P_{j3}^k$ are the probabilities of detection of a situation D_k by the decomposition of the coefficients c_{j1}, c_{j2}, c_{j3}.

For $P_k > P_k^*$, the triplet of the coefficients c_{j1}, c_{j2}, c_{j3} allows to detect a situation D_k with a given probability. Otherwise, the given probability P_k^* of the detection of a situation D_k is unreachable.

4. The resulting set of decomposition coefficients to be monitored, as a rule, is redundant. The algorithm for forming the optimal set of coefficients is as follows. A table of situations is compiled, in which the columns correspond to all possible situations, and the rows correspond to all decomposition coefficients. If the coefficient is informative for detecting this situation, then a true is put in the appropriate cell, if not, false. In the first step, the coefficient with the maximum number of "true" is included in the optimal set. In the second step, the columns of situations that are detected using the first coefficient included in the set are deleted, and the coefficient with the maximum number of "true" in the remaining columns of the table is included in the optimal set. Similar steps are performed until all situations are exhausted. If at one of the steps in the optimal set at least one coefficient from the triple is included, then the other two coefficients from this triple are included.
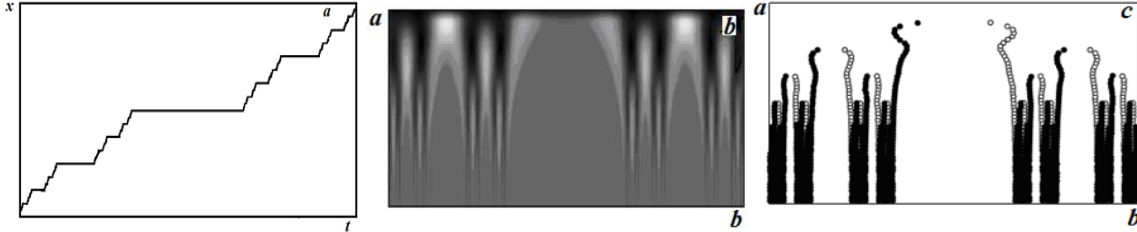
Fig. 2 – Output signal (a) and results of the analysis: the projection of the surface of the wavelet transform coefficients (b) and the skeleton (c). The large values of the wavelet coefficients correspond to the darker areas (b). White circles in (c) are marked with lines of local minima of the surface of wavelet coefficients, and black ones are the local maxima

The diagnostic algorithm itself consists in calculating the current values of the found optimal set of decomposition coefficients and checking whether any coefficient is in one of the intervals $\left(\alpha_j^i, \beta_j^i\right)$. If yes, then according to this feature (or if at least two of the three features coincide when diagnosing a situation by three factors) a decision is made about the presence of a situation D_i. If the values of the coefficients do not fall into one of the intervals $\left(\alpha_j^i, \beta_j^i\right)$, there is a situation of rejection from decision.

The described diagnostic algorithm can be efficiently implemented with the help of the on-board computer (OnCPU) at low time and memory costs or with the help of a specialized calculator at low hardware costs. A priori information required for the above diagnostic procedure can be obtained by calculating the probabilities of various failures, mathematical modeling of the system, and analysis of the errors of the identification algorithm. As a rule, one can accept the hypothesis of the normality of the probability density distributions $f\left(c_j / D_i\right)$.

2.3 Recognition System Visualization

The visualization performance of the recognition system consists in the construction of paintings of the lines of local extremes of the surface or the so-called "skeleton". The corresponding lines are located by determining the coordinates of the points of the space of parameters in which the following equality is performed:

$$\frac{dC(a,b)}{db} = 0.$$

It is believed that this skeleton contains basic information about wavelet transformation, without any superfluous details. For illustration, let's consider a test case – the signal possessing properties of self-similarity (fractal structure) in a wide range of scales

(Fig. 2a). The projections of the surface of the coefficient modules $|C(a,b)|$ on the plane ab and the isolated skeleton are presented in Fig. 2b, c. The calculations used MHAT-wavelet.

Another way of visualizing the most important information about wavelet transformation is to identify the instantaneous characteristics (amplitude, frequency, and phase) of the rhythmic processes. It is often called the construction of "ridges" of wavelet transformation [8]. Ranges are built for the surface $W(a,b)$ and are determined by the formula

$$\frac{d(W(a,b)/a)}{da} = \frac{d\left(|C(a,b)|^2/a\right)}{da} = 0. \tag{8}$$

Instead of a surface $W(a,b)$ it is convenient to consider $W(f,b)$, that is, to make a transition to the frequency representation of the energy spectrum. In the latter case, the derivative in (8) is calculated by. If exclude from consideration the points corresponding to very small values $|C(a,b)|$, which in practice can be related to noisy signal, computational errors, etc. (the threshold is given taking into account the characteristics of the analyzed signal and the noise level), then the obtained ridges, depicted in the form of lines on the plane ab, correspond to the instantaneous frequencies of the rhythms of oscillations present in the analyzed signal.

This is a very convenient and obvious way of analyzing nonstationary multifrequency dynamics, which provides the ability to track the temporal evolution of each rhythm of oscillation of interest to the researcher. In particular, the construction of the ridges allows to analyze the effects of mutual adjustment of instantaneous frequencies when synchronizing interacting self-oscillating systems, characterizing the impact of one system on another, etc. Since each point of the spine is associated with the local energy spectrum, finding the instantaneous frequencies of oscillatory processes simultaneously ensures and determines the instantaneous amplitudes of these processes.

3. ENGINE DYNAMICS CONTROL SYSTEM

Now the scheme of the automatic control system of the GTE is considered.

Fig. 3 illustrates a functional diagram of the control system for the normal operation of the GTE with the following notations: Adjuster; Sensor; R – regulator; Ac
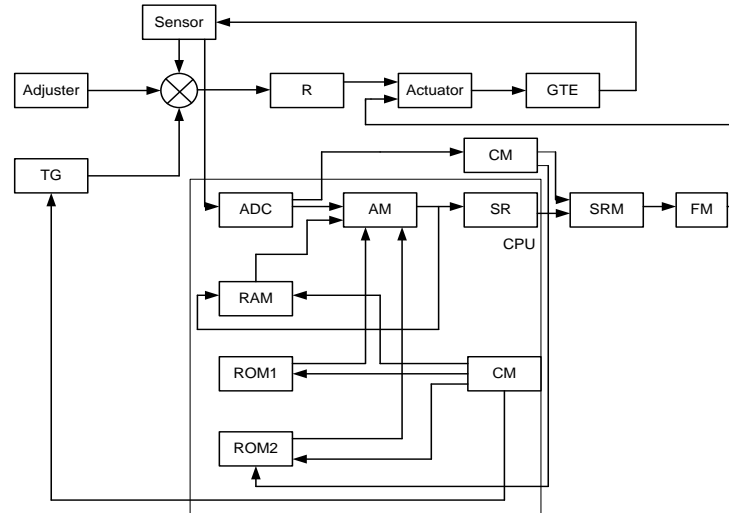
tuator – executive mechanisms; TG – test generator; CM – correction module; SRM – situation recognition module; FM – forming module; CPU – computing processing unit; ADC – analog-to-digital converter; AM – arithmetic module; SR – situation register; RAM – random access memory; ROM1, ROM2 are, respectively, the first and second read-only memory; CM is a control module.

Fig. 3 – Engine control system diagram

This system controls the dynamics of the GTE on one or another channel determined by the parameters (the rotation speed of the GTE rotor, the speed of its change, the air flow pressure by compressor, the gas temperature before the turbine, etc.) or the complex of these parameters. For operating this, test signals of the pseudo-random type (PRS) of limited intensity are fed into the corresponding channels from the test generator TG and the decomposition coefficients of the channel ITF in row by the wavelet functions c_i are calculated.

4. CONCLUSIONS

An essential feature of a definite optimal method for describing a dynamic system is the use of identified wavelet coefficients to control possible violations (failures of elements of ACS aircraft power plant) during operation of the system. Both these tasks – adaptation and control of the system state – can be solved within a single specialized computing device. The developed algorithm includes:

– periodic measurement of the most sensitive decomposition coefficients;

– the classification of the ACS aircraft power plant situations, which correspond to the measured current values of the coefficients, using a certain measure of proximity of the vectors, in accordance with the control rules;

– forming the adjustment signals of the regulator parameters in the presence of normal situations;

– adoption of one or another solution, previously incorporated into the system, in the presence of critical situations.

The correctness of the identification of the instantaneous frequencies is nonstationary. Multi-frequency

modes of oscillation depend not only on the spectral resolution of the selected wavelet, but also on the degree of non-stationary: rapid changes in the characteristics of oscillations lead to the appearance of interference effects that can be mistaken for frequency modulation of oscillations. The analysis of such signals should be accompanied by additional research to confirm the correctness of the evaluations carried out and the correct interpretation of the results.

The proposed control system of the ACS GTE controls the engine dynamics by one or another channel, which is determined by the parameters (rotation speed of the GTE rotor, its rate of change, air flow pressure by compressor, gas temperature before the turbine) or a set of these parameters.

The conducted research shows that at present, insufficient attention is paid to the development of combined information processing methods, combining the advantages of using wavelets and artificial neuron-clear systems, in the scientific works of specialists of this direction, the issue of wavelet-evaluation of random sequences is not covered; the procedure for choosing a maternal wavelet is definitely not formalized, so the wavelet is selected "manually" literally for every specific situation; the mathematical problem of identification is not solved; the training of hybrid networks that are traditionally used has a low convergence rate, which in turn limits their use, especially when working in real time. In this connection, the task of developing methods and algorithms for information processing is based on the joint use of the theory of neural networks, the theory of wavelets, and the theory of fuzzy systems that have an increased learning speed, capable of functioning under a priori and current uncertainty is relevant.

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Вейвлет-розклад для діагностики технічного стану систем автоматичного керування двигуном

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У роботі описуються особливості побудови ефективних і надійних АСК в рамках ідентифікації динамічних характеристик, що дозволяє з однієї сторони, організувати оптимальне керування з адаптацією до змінюваних зовнішніх умов і, з іншої сторони, - приймати своєчасні і правильні рішення при виникненні порушень в силовій установці або в керуючій частині АСК. При використанні такого підходу виникає задача виявлення методів ідентифікації, які дозволяють крім оцінки поточного стану системи здійснювати достовірну і своєчасну діагностику можливих порушень. Пропонується в якості ідентифікованих параметрів використовувати коефіцієнти вейвлет-розкладу характеристик замкненої АСК, які допоможуть уникнути проблему забезпечення відмовостійкості системи. Для підвищення надійності електронних систем автоматичного керування розглядається використання автоматичних систем контролю і діагностики їх стану з метою прийняття керуючих рішень при виникненні несправностей двигуна або керуючої системи. Контроль характерних відмов уже на ранній стадії проектування АСК двигуна дозволяє використовувати АСК як координатора, змінюючи алгоритм керування в критичних ситуаціях при збереженні допустимого рівня якості. Тому подальшим покращенням методів побудови високоефективних АСК є дослідження розглянутих моделей розпізнавання та візуалізації роботи системи з визначенням енергетично активних точок на базі мультифрактального формалізму для опису динамічних систем. На основі алгоритму розкладу вейвлет-коефіцієнтів (математичного опису системи) запропоновано технічне впровадження (структурна схема автоматичної системи контролю) для розробки нано- та мікроелектронних пристроїв системи керування двигуном із властивостями коефіцієнтів впевненості на шкалі розподілу.

Ключові слова: Вейвлет, Електронна система керування, Динамічні характеристики, Відмовостійкість, Мультифрактальний формалізм