8. Promyshlennyj pyleulovitel' – industrial'nyj fil'tr dlya ochistki vozduha ot py-li. URL:https://xn----7sbbidzcq8ah0am6d.xn--p1ai/a246661-pyleulovitel-promyshlennyj-mokrye.html.
9. Pat. 2298438 Rossijskaya Federaciya, Truboprovod dlya podachi gaza v elektrostatiche-skij fil'tr i sistema s elektrostaticheskim fil'trom/M.KAAC; T.DEJVIS; S.LEZER;H.RUSHEVEJH 2008.
10. «OOO «LUKOJL-BUNKER», ocenka vozdejstviya na okruzhayushchuyu sredu//2012- 98-101s.
11. Modina, M. A., Khekert, E. v., Voskanian, A. A., Pismenskaia, Y. v., Epikhin, A. I., & Shkoda, V. v. (2021). Bioindication and biomonitoring assessment of the state of atmospheric air and soil in the study area. IOP Conference Series: Earth and Environmental Science, 867(1). https://doi.org/10.1088/1755-1315/867/1/012072
12. Modina, M. A., Kheckert, E. v., Epikhin, A. I., Voskanyan, A. A., Shkoda, V. v., & Pismenskaya, Y. v. (2021). Ways to reduce harmful emissions from the operation of power plants in special environmental control areas. IOP Conference Series: Earth and Environmental Science, 867(1). https://doi.org/10.1088/1755-1315/867/1/012104
13. Tormashev, D. S. Modern challenges of the marine industry in the field of decarbonization of ships and ways to optimize energy saving processes in SEU / D. S. Tormashev, A. I. Epikhin // Operation of marine transport. – 2021. – № 3(100). – Pp. 110-113. - DOI 10.34046/aumsuomt100/16.
14. Modern requirements in the field of air pollution with sulfur oxides from ships / M. A. Modina, E. V. Heckert, A. I. Epikhin [et al.] // Operation of marine transport. – 2021. – № 3(100). – Pp. 88-91– - DOI 10.34046/aumsuomt100/12.
15. Epikhin, A. I. Carbon-neutral fuel. Possibilities of application in various industries (including marine transport) / A. I. Epikhin, A. A. Ivanchenko, M. R. Neizhmak // Operation of marine transport. – 2021. – № 4(101). – Pp. 161-167. - DOI 10.34046/aumsnom1101/25.
16. Ignatenko, A.V. Reduction of the carbon footprint during operation of dynamically positioned offshore development vessels / A.V. Ignatenko, N. A. Kravchenko, A. I. Epikhin // Operation of marine transport. – 2021. – № 4(101). – Pp. 188-193– - DOI 10.34046/aumsuomt101/31.
17. Epikhin, A. I. Management of toxicity of marine engine exhausts / A. I. Epikhin, Yu. G. Kosolap // Operation of marine transport. – 2020. – № 2(95). – Pp. 66-69. - DOI 10.34046/aumsuomt95/11.
18. Epikhin, A. I. The concept of environmental improvement of marine power plants / A. I. Epikhin, M. A. Modina, E. V. Heckert // Operation of sea transport. – 2020. – № 3(96). – Pp. 127-132– - DOI 10.34046/aumsuomt96/18.
19. Epikhin, A. I. Features of the operation of ship power plants in areas of special environmental control in the context of the introduction of restrictions of the International Maritime Organization in 2020 / A. I. Epikhin, M. A. Modina, E. V. Hekert // Operation of marine transport. – 2020. – № 4(97). – Pp. 67-71– - DOI 10.34046/aumsuomt97/12.

УДК 621
DOI: 10.34046/aumsuomt102/20

DIAGNOSTICS AND INTERPRETATION OF SIGNALS OF A COMPLEX DYNAMIC SYSTEM OF A SHIP POWER PLANT BASED ON FRACTAL ANALYSIS

Ionut Cristian SCURTU, A. I. Epikhin, Octavian Andrei BREZEAN

The article is devoted to the analysis of the features of the diagnostics and interpretation of the signals of a complex dynamic system of a ship power plant (SPP) based on fractal analysis. During the analysis, the Hurst exponent was calculated and the wavelet decomposition of the signals being analyzed was carried out. The proposed approach is universal and can be used to diagnose the technical condition of different types of power plants.

Keywords: fractal analysis, ship power plant, wavelet decomposition, signal, vibration.

ДИАГНОСТИКА И ИНТЕРПРЕТАЦИЯ СИГНАЛОВ СЛОЖНОЙ ДИНАМИЧЕСКОЙ СИСТЕМЫ СУДОВОЙ ЭНЕРГЕТИЧЕСКОЙ УСТАНОВКИ НА ОСНОВЕ ФРАКТАЛЬНОГО АНАЛИЗА

Ionut Cristian SCURTU- PhD in mechanical engineering, Head of Research Department (Romania)
А.И. Епихин, кандидат технических наук, доцент
Octavian Andrei BREZEAN PhD (Romania)

Статья посвящена анализу особенностей проведения диагностики и интерпретации сигналов сложной динамической системы судовой энергетической установки (СЭУ) на основе фрактального анализа. В процессе проведения анализа был рассчитан показатель Херста и осуществлено вейвлет-разложение сигналов, которые анализируются. Предложенный подход является универсальным и может использоваться для диагностики технического состояния СЭУ разных типов.

Ключевые слова: фрактальный анализ, судовая энергетическая установка, вейвлет-разложение, сигнал, вибрация.

Over the past decades, the theory and practice of determining the state and operability of a ship's power plant has been developing by universalizing diagnostic methods and tools, ensuring high efficiency of their use, ensuring optimal distribution of diagnostic functions between various control tools, as well as using complex diagnostic systems, intelligent systems for recording and analyzing diagnostic information.

Currently, world practice has proved that one of the most effective methods for ensuring the operational reliability of equipment, structures and materials is the widespread introduction of new innovative technical means and technologies for assessing the actual state by non-destructive testing and technical diagnostics [1]. Functional diagnostics systems based on the use of diagnostic information obtained directly during the operation of a technical system - data on the parameters and characteristics of dynamic processes-have become particularly widespread and popular today.

There is no doubt that the information signals received during the control process carry much more information about the state of the observed object than the data that are actually used by modern control methods to decide on the presence or absence of a defect and its classification. One of the possible ways to improve the efficiency of systems for diagnosing the state of SPP is to analyze a set of informative parameters of signals, i.e. to conduct multiparametric control, which involves multi-level signal processing with step-by-step application of various analysis methods. This approach makes it possible not only to gradually identify components with low vibrational energy that carry information about changes in the technical condition, for example, element of movement of an individual object of the SPP or the system as a whole, but also to increase the information content or provide a clearer interpretation of the characteristics of the system signals based on fractal analysis.

The use of fractal analysis for diagnosing the technical condition of the power plant will allow to obtain an integral quantitative assessment of the frequency-time spectrum, which can be used to determine the system's performance in the absence or presence of damage to its elements. The use of rotary installations in SPP has great prospects associated with the cost-effectiveness of its operation, improving environmental performance and increasing uptime.

Thus, these circumstances predetermined the choice of the topic of this article.

The study of the features of the use of various methods and tools for diagnosing the technical condition of the SPP was carried out by many domestic and foreign scientists, including Yu.D. Akulshin, R.A. Bullock, V. Veselovsky, A.V. Gorodetsky.

However, with the development of computer technology, it became possible to process more information and use more advanced diagnostic technologies, for example, a neural network classifier for an information-measuring system, cluster and intelligent analysis, genetic algorithms, etc.

In view of the foregoing, the purpose of the article is to consider the features of using fractal analysis for diagnosing and interpreting signals from a complex dynamic system of the SPP within the framework of stationary and transient operating modes.

Most of the processes that occur during the operation of elements of a complex dynamic system of SPP under conditions of long-term dynamic perturbation are characterized by noise-like temporal realizations, a multicomponent composition, and often randomness. In such cases, it is difficult to identify the useful component of the signal, predict changes or classify it. Fractal analysis is one of the promising directions for the study of such time sequences. This is due to its ability to analyze signals, which, from the point of view of correlation or spectral theory, are nothing more than just white noise or Brownian motion [2].

We will consider the features of using fractal analysis using the example of a rotary power ship installation, which was patented in 2017 (protection document number 0002633821) and is positioned for use on ships used to transport liquefied natural gas (LNG).

Rotary SPP consists of main and auxiliary engines. The rotor sections of each of these engines have a body equipped with two adjacent internal cylindrical bores, in which the rotors are mounted on the shafts with the possibility of rotation in opposite directions from the pressure of the working fluid on their protrusions [3, 4, 5]. The main engine and propulsion unit is a propulsion unit operating from an external supply of the working fluid, the propulsion unit of which can be located outside the ship's hull with the possibility of changing the immersion depth, position, elevation angles from the water and inclination in field conditions.

Figure 1 shows a diagram of the ship's rotary power plant.

To diagnose the technical condition of a rotary power plant, we will consider the operation of the rotor, which is equipped with rotary-ball elements. Rotary power plant in the course of its operation carries out forced and resonant vibrations, that is, it exhibits vibrational activity. The intensity of oscillations of mechanical origin, and, consequently, the vibration of the motor housing are determined by the state of the rotors, their support bearings, the rigidity of the supports, i.e. the state of the engine [3]. Thus, the measurement and analysis of vibration parameters makes it possible to assess the technical condition of each element separately and of the entire engine as a whole. The high information content of vibroacoustic signals, the simplicity of their conversion into electrical signals and, therefore, the possibility of automating the entire process of monitoring and diagnosing make it possible not only to detect, but also to prevent in advance the malfunctions of the rotary power plant as a whole.

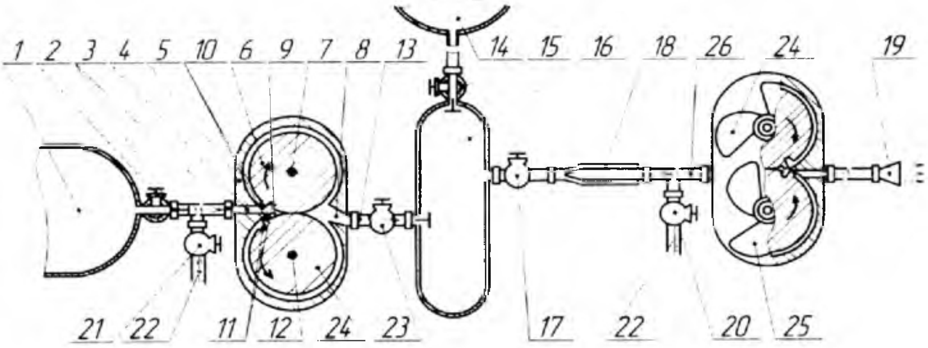
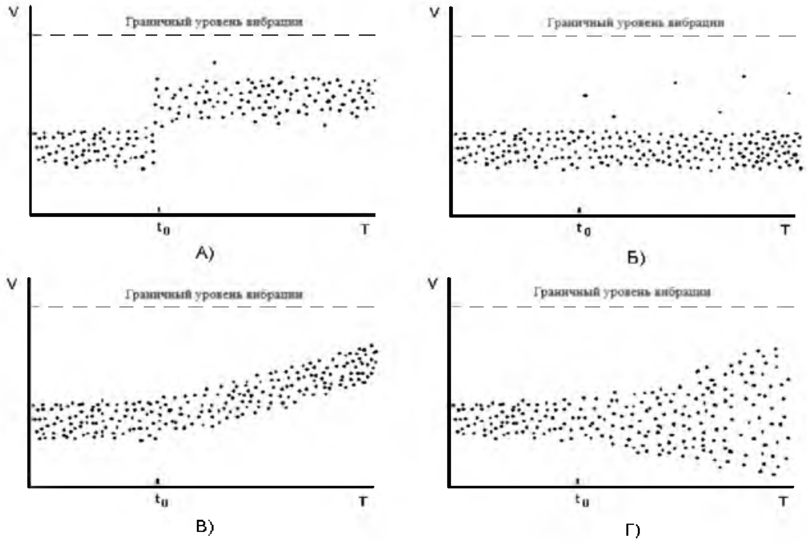


Fig. 1 Rotary ship power plant [3]
1 - high pressure tank; 2 - shut-off and control valves; 3 - flanges; 4 - channel for supplying the working fluid; 5 - body; 6 - rotor, 7 - shaft; 8 - exhaust gas outlet channel; 9 - working chamber; 10 - protrusions (elements that form the working chamber); 11 - hollows; 12 - shaft; 13 - channel for the transition of the working fluid from one section to another; 14 - capacity for the accumulation of evaporating gas; 15 - locking and adjusting device; 16 - low pressure tank; 17 - locking and adjusting device with a gearbox; 18 - external combustion chamber; 19 - nozzle; 20, 21, 23 - locking and adjusting device; 22 - channel for the transition of the working fluid; 24, 25 - propellers

As practical experience shows, in many cases, at the moment of the beginning of the development of a malfunction (t_0), the root-mean-square vibration values (V) do not reach the established warning or emergency limits (Fig. 2), therefore, vibration monitoring systems built on a rigid tolerance loop do not issue any signals to the operator. But, as can be seen from Fig. 2, the measurement information, starting from the moment t_0, carries diagnostic signs of a malfunction.



Rice. 2 Change in the root-mean-square values of vibration over time
(*V* – vibration level, *T* -time, t_0 - the moment of the beginning of the fault development)
A) - an abrupt increase in the mathematical expectation of the vibration level; B) - the appearance of "emissions" of the vibration level; C) - the growth of the mathematical expectation of the vibration level; D) increase in the standard deviation of the vibration level

As a model of rotary-ball elements, we will consider oscillatory systems with one degree of freedom, which in the simulation scheme are given by their impulse characteristics. The natural frequency is assumed to be the same for all elements

$\omega = 628$ sec^{-1} (f = 100 Hz).

Vibration disturbance in the stationary mode of operation is given by a polyharmonic signal model, the main component of which is the first rotor harmonic (component at the rotor speed ω_p). Let us consider two modes of stationary vibration disturbance: mode 1 - with additional superharmonic components at frequencies that are often multiples of the main rotary harmonic $\omega_{pi} = i \times \omega_p$, (i = 2, 3); mode

2 - with additional subharmonic components (i =1/2;1/3). Vibration perturbation will be formed for the following data: rotor speed ω_p = 1570 sec^{-1}; the ratio of the amplitudes that make up vibrations for mode 1 is:

P_1: P_2: P_3 = 1:10^{-2}: 10^{-3}, a 2 - P_1: $P_{1/2}$: $P_{1/3}$ = 1:10^{-2}: 10^{-3}.

In the transient mode, in the vibration disturbance model, we take into account the linear change in the rotor speed. The instantaneous value of rotational speed is defined as $\omega_p(t) = \omega_0 + \beta t$, where ω_{p0} is initial speed value, and β - is the rate of change of rotor speed. As for a stationary perturbation, we will consider perturbation regimes with additional superharmonic components. Vibrational perturbation will be formed for the following data:

ω_{p0} = 220 sec^{-1}; β = 110 sec^{-2}.

The determination of the statistical estimate of the mathematical expectation of the vibrational parameter Y_1, calculated at the i-th measurement, is carried out according to the formula:

$$\bar{Y}_i = \frac{\sum_{i=1}^{n} Y_i}{n}$$

where Y_i is the result of the i-th measurement of the vibration parameter.

n - number of dimensions.

Determination of the statistical estimate of the variance D_i and the standard deviation S_i of the registered values of the vibration parameter is carried out using the formulas:

$$S_i = \sqrt{D_i} \qquad D_i = \frac{\sum_{i=1}^{n} (Y_i - \bar{Y}_i)^2}{n-1}$$

Determination of the upper and lower limits of statistically possible values of vibration parameters is calculated as follows:

$$Y_i^{*B} = \bar{Y}_i + k_i S_i \qquad Y_i^{*H} = \bar{Y}_i + k_i S_i$$

Calculation of the weighted average standard deviation of the levels of vibration parameters of serviceable engines S_m is based on the use of statistical information for the entire fleet of the same type of rotary engines:

$$S_m = \sqrt{\frac{\sum_{i=1}^{m} S_{in_i}^2 (n_i - 1)}{(\sum_{i=1}^{m} n_i) - m}}$$

where m is the number of serviceable engines;

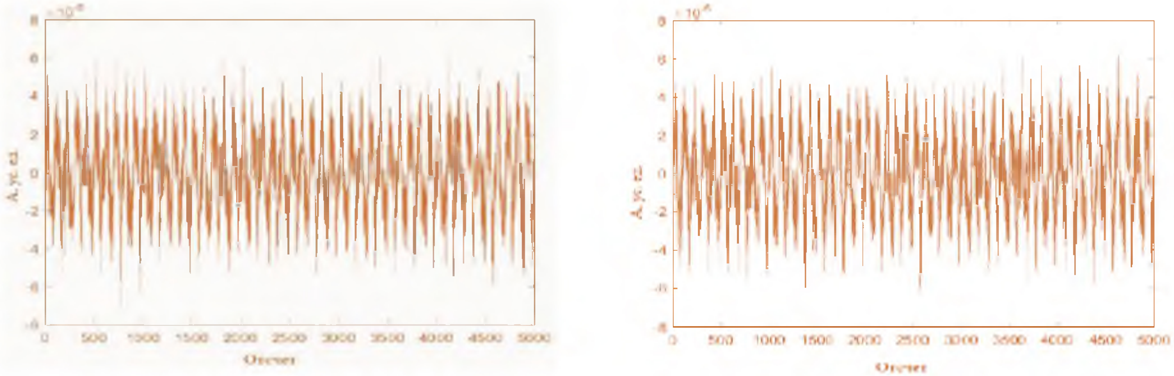
n_i - number of measurements on the i-th serviceable engine;

$S_{in_i}^2$ - dispersion of vibration levels of the i-th motor for n_i measurements.

The formation of vibration signals at the output of the model of the rotary SPP was carried out by convolution of the impulse characteristics of the rotor-ball elements and the corresponding input vibration disturbance. The obtained vibration signals were used for further analysis without taking into account and taking into account additive noise (stationary Gaussian noise) with a zero mean value. The noise dispersion value was set in such a way as to provide such values of the signal-to-noise ratio ρ = 16 and ρ = 16×10^2.

The simulation of vibration signals was carried out on a time interval t=5 sec, the sampling period $\Delta t = 1\times10\text{-}4^{-4}$ sec (sampling frequency f_o = 10 kHz), the time realizations contain N = 5×10^{-4} points.

A sample of the simulated vibration signal (N = 5000 points) in mode 1 of the vibration disturbance with allowance for additive noise (ρ=16) is shown in Figure 3.On the ordinate axis, the amplitude values are plotted in conventional units, and on the abscissa axis, the time in counts is plotted [6, 7, 8]. A sample of the simulated vibration signal (N = 5000 points) in mode 2 of the vibration disturbance taking into account additive noise (ρ=16) is shown in Figure 3.



Mode 1

Mode 2

Fig. 3. Sampling of the vibration signal in modes 1 and 2 of the vibration disturbance taking into account the additive noise (ρ=16)

For complete realizations of vibration signals obtained at the output of the model of rotary-ball elements, for each of the above vibration disturbance modes, with and without additive noise of various intensities, an R/S analysis was performed and the values of the Hurst exponent were determined. The results obtained are presented in Table 1.

Table 1 - The value of the Hurst exponent of vibration signals at the output of the model of rotor-ball elements of the SPP

Vibration disturbance mode	No noise	With aditiv noise	
		$\rho = 16\times10^2$	$\rho = 16$
Mode 1	0.1416	0.2540	0.6752
Mode 2	0.1189	0.2456	0.6698
Mode 3	0.1088	0.1746	0.4977
Mode 4	0.1061	0.1711	0.4963

As can be seen from the obtained results, the Hurst exponent for simulated signals in all modes of vibrational disturbance of the rotor system of the SPP without taking into account additive noise lies in the range $0<H<0.5$. According to the information in Table. 1, this range of indicator values characterizes the antipersistence of the time series parameters that are analyzed.

A more detailed fractal analysis of vibration signals can be performed by applying signal preprocessing, for example, using a wavelet decomposition into a hierarchical set of approximations A_i and details D_i (i is the number of decomposition levels). The following parts are selected: flanges (D_1), shaft (D_2), protrusions (D_3), depressions (D_4), storage tank for evaporating gas (D_5), shut-off and adjustment device (D_6).

For the obtained decomposition elements at the second stage, the Hurst exponent is determined, as for individual implementations. On Figure 4 shows the results of the wavelet decomposition of the vibration signal obtained with stationary vibration excitation (mode 1) without taking into account additive noise. For decomposition, the Daubechies db10 wavelet was chosen, the decomposition was carried out into 6 levels. The ordinate shows the amplitude values in arbitrary units, and the abscissa shows the time in counts [9, 10, 11].

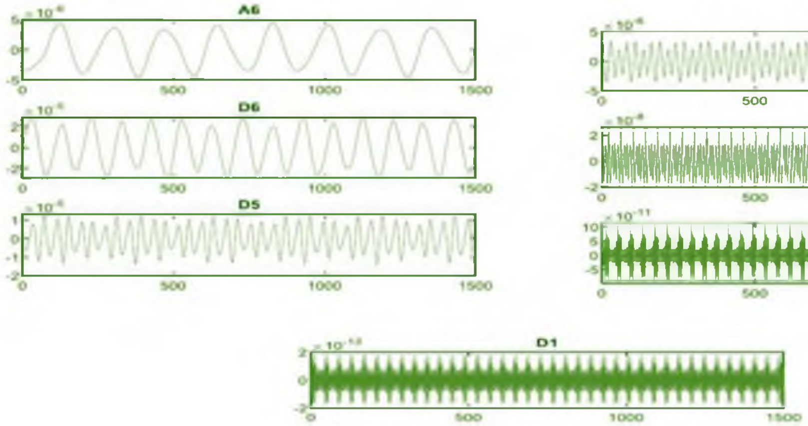


Fig. 4 Elements of the wavelet decomposition of the vibrational signal in mode 1 of the vibrational disturbance without taking into account the additive noise (fragment of length N = 1500 points)

Thus, the approach proposed in the paper to the fractal analysis of diagnostics and interpretation of the signals of a complex rotor system of the SPP allows, using the mathematical apparatus, to build the statistical boundaries of the root-mean-square vibration level, which are adaptive and make it possible to quickly identify a malfunction at the early stages of its development. In addition, in the course of the study, the dependences of fractal characteristics on vibrational disturbance modes, as well as the presence and intensity of additive noise, were established. For a more detailed study of the technical state of the SPP rotor system, it is proposed to determine the fractal characteristics of the elements of the wavelet decomposition of the signal being analyzed.

The proposed approach is universal and can be used to diagnose and analyze the technical condition of power plants, which are based, for example, on a diesel plant. In this case, the turbine, compressor, crankshaft, cylinder, piston, that is, all the details of the movement, can act as the observed parameters.

Literature:

1. Kalikatzarakis, M. et al. Ship energy management for hybrid propulsion and power supply with shore charging // Control engineering practice. 2018. Volume 76; pp 133-154.
2. Sorensen, Asgeir J. et al. Toward Safer, Smarter, and Greener Ships Using hybrid marine power plants // IEEE electrification magazine. 2017. Volume 5: Issue 3; pp 68-73.
3. Kwaśniewski, Tomasz Design analysis of hybrid gas turbine—fuel cell power plant in stationary and marine applications // Polish maritime research. 2020. Number 2; pp 107-119.
4. Kondratiev S.I. Ensuring the safety of navigation of transport vessels in the port when maneuvering in the operating water area of the berth [Text] / S.I. Kondratiev, V.V. Ustinov // Transport business of Russia. 2012. No. 6-2. pp. 196-197
5. Epikhin A.I., Hekert E.V., Modina M.A.Principles of neurocontrol and architecture options for neural

networks, as applied to a complex dynamic system of SPP-shipMarine intelligent technologies. 2020. No. 4-4 (50). pp. 18-22.

6. Kondratiev S.I. Methods for calculating characteristic polynomials in problems of control of moving objects. Textbook / S. I. Kondratiev, G. A. Zelenkov // Federal state. educational institution of higher education prof. education "Marine State Academician named after Admiral F.F. Ushakov". Novorossiysk, 2007.
7. Engovatova V.V., Dmitrenko E.V., Shkoda V.V., Solonnikova N.V., Modina M.A. Life safety and labor protection of workers of industrial enterprises. Part 2. Study guide / Krasnodar, 2020.
8. Studenikin D.E., Bovan S.D., Hekert E.V., Modina M.A.Using neural networks to organize visual observation//Marine intelligent technologies. 2019. No. 4-3 (46). pp. 91-95.
9. Studenikin D. E., Kondratiev S. I., Hekert E. V., Modina M. A. Dynamic formation of a safety corridor when planning a ship's route // Marine Intelligent Technologies. - 2021. - T. 4. - No. 2 (53). - S. 128-131. – DOI 10.37220/MIT.2021.52.2.081.
10. Studenikin, D. E. Some aspects of vessel's movement in congested waters analysis for preliminary route planning / D. E. Studenikin, S. I. Kondratev, M. L. Javuktsyan // Marine transport operation. - 2019. - No. 3 (92). – P. 30-34. – DOI 10.34046/aumsuomt92/5.
11. Boran-Keshishyan, A.L., Astrein, V.V., Kondratiev, S.I. Formalization of the general decision-making strategy to achieve the ship's integrated safety, Marine Intelligent Technologies. - 2019. - No. 1-2 (43). - S. 127-131.

УДК 621.431.7
DOI: 10.34046/aumsuomt102/21

DEVELOPMENT OF NEURAL NETWORKS FOR PREDICTING THE RISK OF FAILURE OF COMPONENTS OF SHIP MACHINES AND MECHANISMS OF MARINE AUTONOMOUS SURFACE VESSELS

Ionut Cristian SCURTU, A.I. Epikhin, E.V Khekert

The article discusses the possibilities of applying neurocybernetics approaches for the implementation of intelligent prediction of the risk of failure of components of ship technical means of autonomous sea surface ships. In the course of the research, a method was proposed that allows one to build a formal model of the observed units and equipment of ship installations based on the tasks of classification and pattern recognition. An algorithm for the initialization of a neural network is also proposed, which makes it possible to achieve a given accuracy of determining the parameters of the operation of technical means, which makes it possible to provide flexibility in setting up management of emerging risks based on predetermined criteria.

Key words: risks, units, equipment, vessel, forecasting, management.

РАЗРАБОТКА НЕЙРОННЫХ СЕТЕЙ ДЛЯ ПРОГНОЗИРОВАНИЯ РИСКА ВЫХОДА ИЗ СТРОЯ КОМПОНЕНТОВ СУДОВЫХ ТЕХНИЧЕСКИХ СРЕДСТВ МОРСКИХ АВТОНОМНЫХ НАДВОДНЫХ СУДОВ

Ionut Cristian SCURTU - PhD in mechanical engineering, Head of Research Department (Romania)
А.И. Епихин, кандидат технических наук, доцент
Е.В. Хекерт, доктор технических наук, профессор

В статье рассмотрены возможности применения подходов нейрокибернетики для осуществления интеллектуального прогнозирования риска выхода из строя компонентов судовых технических средств морских автономных надводных судов. В процессе исследования предложен алгоритм, который позволяет построить формальную модель рисков отказа наблюдаемых узлов и оборудования судовых установок на основании задач классификации и распознавания образов. Также предложен алгоритм инициализации нейронной сети, благодаря которому может быть достигнута заданная точность определения параметров работы технических средств, что дает возможность обеспечить гибкость настройки управления возникающими рисками на основании заранее определенных критериев.

Ключевые слова: риски, узлы, оборудование, судно, прогнозирование.

The current level of organization and management of ship technical facilities, which are a complex dynamic system consisting of many interacting elements and subsystems, puts forward increased requirements for the development of new approaches based on the use of advanced information technologies and intelligent support and decision-making tools [1, 4, 5, 14].

A wide range of instrumental methods and approaches to monitoring, analyzing, diagnosing and predicting the technical condition of ship equipment, as well as the risks of its failure, has a significant drawback, which lies in the fact that their use is possible only with a certain frequency, in accordance