INDUSTRY CONTROL SYSTEMS

Аналіз відмов газоперекачувальних агрегатів (ГПА), встановлених на трансконтинентальному газопроводі «Уренгой-Помари-Ужгород» показав, що відмови систем автоматичного управління (САУ) ГПА займають друге місце (до 40 %) від загальної кількістю відмов. Показано, що відомі методи контролю технічного стану механічної частини ГПА не можуть бути використані для контролю працездатності САУ і елементів автоматики ГПА. Серед відомих методів контролю працездатності САУ ГПА, як динамічної системи, найбільш перспективними є методи, що базуються на аналізі її перехідного процесу (розгінної характеристики) при деякому типовому вхідному впливі.

Приведене теоретичне обгрунтування розробленого методу контролю працездатності САУ ГПА, діагностичною ознакою якого є значення площ розгінних характеристик. Структура передавальної функції та її параметри визначалися методом площ (метод Симою). Для реалізації методу у середовищі MatLab розроблено програмне забезпечення, яке дає змогу визначити параметри функції передачі за експериментальною кривою пуску ГПА та величину площі, яка обмежена його перехідною функцією.

Наводиться методика проведення експериментальних досліджень запропонованого методу контролю працездатності САУ ГПА на прикладі ГТК-25і, яка дозволила отримати дев'ять розгінних характеристик ГПА в координатах «час – частота обертання ротора ТВТ» та результати їх обробки.

Подальша реалізація запропонованого методу вимагає визначення умов його працездатності та паралельного контролю технічного стану механічних вузлів ГПА з метою виключення їх впливу на результат контролю стану САУ ГПА

Ключові слова: газоперекачувальний агрегат, система автоматичного управління, розгінна характеристика, технічний стан

DEVELOPMENT OF THE METHOD FOR ESTIMATING THE TECHNICAL CONDITION OF GAS PUMPING UNITS BY THEIR ACCELERATING CHARACTERISTIC

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1. Introduction

The gas transmission system of Ukraine (GTS) is one of the largest in the world both in terms of length and volume of gas transit. It consists of 78 compressor stations (CS) (121 compressor workshops) with a total capacity of 5492 MW with operating 779 gas pumping units (GPU) of twenty types, both domestic and foreign production [1]. Among them is the transcontinental gas pipeline Urengoy-Pomary-Uzhorod, which is one of the main gas pipelines of the GTS. Its diameter is 1400 mm, and the throughput is 30 billion m³. About 130 gas pumping units type GTK 25-i manufactured by Nuovo Pignone (Italy) are in operation, 30 of which are in "Ukrtransgaz" JSC. The long period of GPU operation (more than 30 years) has led to the fact that a significant percentage of GPU in JSC "Ukrtransgaz" has worked out its installed engine life or is close to it. Further operation of the gas pumping unit leads to a deterioration in their technical condition and, as a consequence, the occurrence of failures and emergency situations. Fig. 1 shows the GPU failure statistics for "Ukrtransgaz" JSC for 2009 by type of equipment. The analysis of defects in the main units of the gas pumping unit during operation showed that the main part of emergency stops and forced downtime associated with defects in mechanical equipment. At the same time, the duration of emergency recovery work can be up to two to three months (at some gas pumping units significant breakdowns of the main units are repeated repeatedly). The cost of such work, depending on their complexity and the complexity of the GPU that failed, can reach significant financial costs.

The second place in the number of failures (Fig. 1) is occupied by automatic control systems (ACS) and automa-

tion – up to 40 %. At the time of commissioning, automatic control systems of gas pumping units were developed on a modern, at that time, elemental base by leading world manufacturers – General Electric (GE), Nuovo Pignone, Allgemeine Elektrizitäts-Gesellschaft (AEG). The long period of their operation revealed a number of shortcomings and miscalculations, the number of which increased due to the physical and moral aging of the hardware and software of automatic control systems. All this led to malfunctions in their work and, as a result, to false emergency stops of the gas pumping unit and compressor station.
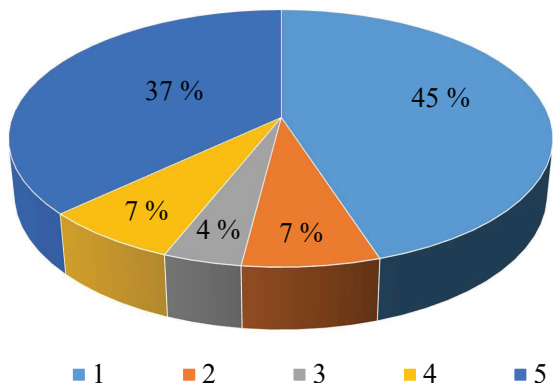

Fig. 1. GPU failure statistics for "Ukrtransgaz" JSC by equipment types in 2009: 1 — mechanical equipment, 6 units; 2 — the type of equipment that failed is not determined 9 units; 3 — equipment failure due to erroneous personnel actions 6 units.; 4 — electrical equipment 10 units; 5 — instrumentation and automation 50 units

Surveys of automatic control systems at the compressor stations operating on the main export gas pipelines showed [2] that they are physically and morally obsolete, have worked out their passport resources twice and require immediate replacement. Such a replacement of automatic control systems for gas pumping units requires significant financial costs (for example, in 2004 the cost of one automatic control system was 4 million UAH), and temporary – it lasts at least a year on shut-down technological equipment. Therefore, specialists of the service of instrumentation and automation of the compressor station develop and implement engineering and technical solutions that extend the life of automatic control systems of gas pumping units. In particular, in [2] there is a list of engineering solutions implemented by the specialists of the CS "Bogorodchany" for automatic control systems of GPU type GTK-25-i and automatic control systems GPA-10-i, which allowed to extend their service life. And also to adapt modern microprocessor automation equipment with existing transistor-relay control systems and reduce the number of false emergency stops of technological equipment.

The introduction of such measures, as well as the replacement of obsolete automatic control systems with modern ones built on a new element base, does not guarantee an increase in their reliability during operation. As an example, Table 1 shows the statistics of failures of automatic control systems for JSC "Ukrtransgaz" during 2012-2019. Failures of 21 GPU tupe GTK-25-i were analyzed, equipped with the standard Speedtronic system and a new automatic control system such as Compressor Controls Corporation (CCC). As can be seen from the Table 1 in 2014-2015, the number of failures of new automatic control systems of the CCC type

exceeded the number of failures of standard speedtronic automatic control systems. Speedtronic automatic control systems are equipped with GPU type GTK-25-i and GTK-10. There is no separate statistics on MTBF for GPU type GTK-25-i, however, from operating experience, taking into account typical defects, MTBF is almost identical in automatic control systems GPU type GTK-25-i GTK-10-i. Regarding failures of automation equipment (Table 1), there is no general trend towards a decrease in the number of failures by year, the exception is 2019 (first half). As for other types of automatic control systems – ATTIZ (Inek), Dawn-1. Ukrgaztekh, Ukrgasgeoavtomatika, LLC Gasprominovatsii, which are equipped with various types of gas pumping units, 41 out of 240 working automatic control systems failed.

Table 1

Failure statistics for automatic control systems of GPU type GTK-25-I for Ukrtransgaz JSC

Years	2012	2013	2014	2015	2016	2017	2018	2019
Type of automatic control system	The number of failures by year							
Speedtronic	5	7	1	1	4	12	5	3
CCC	–	1	3	2	3	5	2	–
The total number of failures of automation equipment for JSC "Ukrtransgaz"	39	46	44	35	44	53	41	25

Thus, neither the introduction of engineering and technical solutions that extend the life of the automatic control systems of a gas pumping unit, nor the replacement of an automatic control system of an obsolete type with a new one leads to an increase in the reliability of a gas pumping unit.

In [3], a detailed analysis of the current state of the reliability assessment of automatic control systems of gas pumping units was carried out. It showed that today, when solving various reliability problems, they use solutions based on the use of various theoretical models of reliability, which lead to a significant discrepancy in the results.

Based on the foregoing, the scientific task of developing a method for monitoring and diagnosing the technical condition of both the mechanical part of the gas pumping unit and its automatic control system is relevant. The solution to this problem will allow for repair work on their actual technical condition and will ensure the reliability and efficiency of the GPU and their automatic control systems.

2. Literature analysis and problem statement

Today, a large number of scientific papers are known on the development of methods for diagnosing the technical condition of the mechanical part of a gas pumping unit during their operation. Using these methods, three diagnostic tasks are solved: monitoring of working capacity (degree of working capacity), defects, predicting the technical condition, or a combination of these tasks. All known methods for the diagnosis of GPU can be divided into two large groups [4].

– parametric diagnostic methods based on processing and analysis of technological parameters characterizing the operation of the gas pumping unit;

– methods of vibroacoustic diagnostics based on the processing and analysis of vibroacoustic vibrations generated

by the units and elements of the GPU during operation and carry information about its technical condition.

When developing a diagnostic method, the main task is to select a diagnostic sign of the state of the gas pumping unit (parameter or characteristic), the change of which characterizes the change in the technical state of the gas pumping unit. Diagnostic signs are selected as a result of the analysis of the diagnostic model.

A significant amount of scientific work has been devoted to the methods of vibroacoustic diagnostics of GPU [5–12]. So, in [5], models of oscillatory processes, mainly of a GPU blade apparatus, are considered, methods for its diagnostics and technical means for their implementation are proposed. The presented models do not allow evaluating the vibrational state of the gas pumping unit as a whole and its effect on the operation of the automatic GPU. In [6], the theoretical foundations of the dynamic characteristics and vibration of gas pumping units and compressor units are considered, on the basis of which diagnostic signs of the technical state of their components and elements are developed. At the same time, the relationship of the influence of changes in the technical condition of individual gas pumping units (high-pressure turbines and low-pressure turbines, axial compressors) on the technical condition of power elements – bearings, or the state of the combustion chamber, also determines the efficiency of the gas pumping units process and the state of the automatic control unit of the gas pumping unit which controls this process. An analysis of the spectra of vibrational and acoustic signals (noise) of the GTK-25-i axial compressor constructed using the Welch method is given in [7]. The purpose of the analysis is to identify diagnostic signs of its technical condition. It is established that acoustic vibrations are more informative, characterized by a wide continuous spectrum with individual discrete components. At the same time, GPU automation tools do not always adequately respond to sharp changes in the amplitude components of the acoustic spectrum of the axial compressor oscillations, which can lead to emergency situations. This requires the study of this phenomenon and the development of a method for monitoring the state of automation. Studies to determine the technical condition of the compressor blades and the turbine engine, which are analyzed both as individual components and as part of the impellers, are given in [8]. The paper also considers the analysis of welds of the combustion chamber by the method of free vibrations. Informative parameters characterizing the oscillatory process are determined, and methods for identifying defects in the components of the gas pumping unit are developed. However, the paper does not indicate how the significance of the studied informative parameters of the state of the axial compressor, low pressure turbine, and combustion chamber is affected by the oscillating processes generated by the gas turbine power elements and the supercharger turbine, and how the automatic control system of the gas pumping unit responds to these changes. In [9], a brief review and comparison of various transformations that can be performed when processing the vibration of an air compressor to evaluate its three states is given. The following transforms were used: fast Fourier transform, discrete cosine transform, autocorrelation function, Cohen class distributions, S-transforms and various wavelet transforms. At the same time, the question of the information content of these transformations for the three considered states of the air compressor and the reaction to them of the automatic control system of the gas pumping

unit was not considered. An algorithm for diagnosing faults in an air compressor based on the use of wavelet transform and artificial neural networks is considered in [10]. At the same time, there are no links in the work of the results of the practical implementation of the developed algorithm with the employer of technical means or as part of the GPU automatic control system. In [11], the problem of determining the influence of the GPU-16R "Ufa" design on its wave gas dynamics, as well as the identification of diagnostic signs of defects in engines during operation, was solved. To solve this problem, let's use numerical methods for modeling wave processes in combination with methods for studying vibration. The task was considered without taking into account the influence of dynamic processes in the gas pumping unit on the state of its automatic control system, the change of which can lead to a false positive of the gas pumping unit protection systems. In [12] proposed a combination of discrete wavelet transform and envelope analysis to extract the characteristic spectrum of vibration bearing data. Then the spectrum cross-correlation coefficient is used to determine the various operating conditions of the rolling bearings and its technical condition. The work did not study the vibrational state of the GPU blade apparatus with the aim of taking it into account when determining the state of rolling bearings, which would improve the reliability of diagnostics of their condition. At the same time, the relationship of the operating conditions of rolling bearings with the GPU operation algorithm, which is implemented by its automatic control system and determines the GPU operation efficiency, has not been considered.

No less scientific papers [13–18] are devoted to parametric diagnostic methods. So, in [13] it was shown that information integration methods, such as Bayesian networks, fuzzy logic or probabilistic neural networks, can be used to implement a decision support system that can be used for parametric diagnostics of gas turbines. At the same time, the proposed decision support system does not contain information about the technical condition of the automatic control system of the gas pumping unit and does not allow using it to monitor the operability of the automatic control system. The method of parametric diagnostics of the state of a gas turbine power plant, based on the identification of the state of its components (compressor, combustion chamber, turbine) using a mathematical model of work processes presented in the form of an artificial neural network model, was considered in [14]. The method allows to identify defects at an early stage of their development, even if the values of technological parameters are within acceptable limits. Moreover, the issue of monitoring the state of the automatic control system as an integral component of a gas turbine power plant, without which it can't function, is not considered. Based on the basic principles of gas turbines and Fisher discriminant analysis (FDA), a new indicator for detecting malfunctions of hot components in gas turbines is presented in [15]. Its use allows avoiding interference associated with uncertainty and increasing the sensitivity of early detection of malfunctions in the hot components of a gas turbine. The task posed in the work was considered without taking into account both the state of the combustion chamber and the automatic control system, on which the efficiency of the turbine depends. In [16], a method for parametric diagnostics of the state of a two-flow turbojet engine based on the identification of the state of components (compressor, combustion chamber, turbine) using a mathematical model of a workflow presented in the form of an artificial neural network model similar to [14] is considered. The state parameters of the engine components are integral criteria

that make it possible to identify its technical condition with a high degree of reliability. The sequence of development of the model and the results of the study of its characteristics during parametric diagnostics of the state of the engine are presented. The disadvantages of the work are similar to [14]. The methods of diagnosing defects in the gas path of gas turbine units (GTU) are the subject of [17, 18]. A new methodology for the classification model for diagnosing faults in the gas path of a gas turbine in the form of a probabilistic neural network (PNN) is considered in [17]. It is compared with previously proposed methods, the results of which show that PNN is not inferior to other methods. In [18], a new combined method was proposed based on an artificial neural network and a support vector machine for diagnosing the gas path of a two-shaft gas turbine engine. The test results showed that the proposed method can be used to diagnose multiple malfunctions of gas turbines with limited measurements of technological parameters. Diagnosing the technical condition of the gas path of the gas-turbine set-up using the methods considered [17, 18] is carried out without taking into account the technical condition of other components of the gas-turbine set-point, including its automatic control system, which can affect the diagnostic result, which requires additional research.

One of the promising diagnostic methods that can be attributed to the two groups considered above remains identification methods, a brief analysis of which is given in [19]. Parametric identification methods can be used to monitor the performance of the automatic control system of the gas pumping unit. In this case, the diagnostic sign is the parameters of the diagnostic model of the automatic control system, which can be represented in the form of differential equations. A variety of diagnostic models based on differential equations is the transfer function.

The transfer function determines both the qualitative and quantitative sides of the change in the state of the system of automatic control. The structure of the transfer function determines the qualitative aspects (the fluctuating, aperiodic nature of the process), and its parameters determine the quantitative changes occurring in the automatic control system.

In practice, both the amplitude frequency $A(\omega)$ and phase frequency $\varphi(\omega)$ characteristics and the real $Re(\omega)$ and imaginary $Im(\omega)$ components of the transfer functions are widely used as an option for the operability of the automatic control system. Most often they use frequency characteristics $A(\omega)$ and $\varphi(\omega)$, which are suitable for assessing the quality of functioning of both linear and non-linear (at least in the framework of harmonic linearization) systems and have high informational properties. With the known structure of the controlled system, they can be determined by the characteristics of the simplest dynamic elements.

In many cases, it is advisable to assess the state of a dynamic system based on an analysis of its transient process with a certain typical input action, as a rule, this is a single jump.

For objects whose dynamics is described by differential equations of no higher than second order, the model parameters are determined directly from the acceleration characteristic. This method of determining the parameters of the model can be successfully applied in cases where the object (to which GPU can be attributed) is under the influence of insignificant interference. In [19], a method was proposed based on the procedure for determining the areas of k-th orders through the moments of an auxiliary function, which allows one to determine both the parameters and the structure of the transfer function. The paper presents the results of testing the method for de-

termining the dynamic properties of a gas pumping unit with an automatic control system without reference to its technical condition. Using a method for identifying the transfer function coefficients of a closed dynamic system by exposing it to a test signal in the form of a single jump, a method for monitoring and diagnosing failures of an automatic control system of a gas pumping unit was proposed in [20]. The system reviews are recorded in the transient completion time interval. By processing registered system reviews with the corresponding computational algorithm, identification, monitoring and diagnostics of its failures is carried out. In the general case, the controlled transfer function coefficients of the closed-loop system are expressed in terms of the diagnostic parameters in the form of nonlinear equations, which complicates their calculation and, accordingly, the process of diagnosing the technical condition of the automatic control system of a gas pumping unit.

The combination method of control and diagnostics of the automatic control unit of the gas compressor unit is based on the use of a general identification algorithm in the space of variables, which are the transfer function coefficients [21]. It allows to obtain integral information that provides an assessment of the performance monitoring and failure detection in the system under study by constructing fault tables. Algorithms for monitoring and diagnostics based on the combinational method are able to provide monitoring of operability and detection of failures of the parameters of all functional units of the systems under study. At the same time, the work does not present the results of testing the method, which does not allow to evaluate its effectiveness and practical application possibilities. The sequential method for monitoring and diagnosing failures of the automatic control system of a gas compressor proposed in [22] is based on a modified identification algorithm. It allows synchronizing with the identification process to monitor and diagnose failures in real time without building fault tables, and provides high speed algorithms implemented on its basis. The authors note that the method is informative compared to the combination method, since the information on each monitored and diagnostic coefficient seems to be autonomous and synchronous with the identification process. Such information includes coefficients characterizing the static properties of the system, and parameters of the polynomials of the numerator and denominator of the transfer function, characterizing the dynamic properties of the system. However, there are no results of practical confirmation of the effectiveness of the proposed method. The method of diagnosing a GPA automatic control system based on their decomposition based on the identification of the transfer function of the entire system as a whole, followed by decomposition of the obtained transfer function and the transfer function of the system's functional units [23]. During identification, a common record of the system transfer function is used, and identification is carried out in a single experiment in an automated mode, while the coefficients of the polynomials of the numerator and denominator are sequentially determined. In the construction and implementation of monitoring and diagnostic algorithms, the hypothesis of the unlikely occurrence of two or more simultaneous failures of the parameters, the functional units of the system within the identification period is accepted, which is confirmed by the corresponding calculation of the probability of occurrence of failures. Confirmation of the operability of this method requires its experimental verification.

The analysis shows:
– when developing methods of vibro-acoustic and parametric diagnostics, as a rule, of mechanical components and compo-

nents of a gas compressor unit – a vane apparatus, a combustion chamber, power elements (bearings), the condition of an axial compressor, a high-pressure turbine, a low-pressure turbine, etc. researchers focus on identifying diagnostic signs their condition. For this, the conversion of vibro-acoustic signals and technological parameters for the purpose of their further processing is carried out using the fast Fourier transform, discrete cosine transform, autocorrelation function, Cohen class distribution, S-transform and various wavelet transforms, etc. Processing of the obtained data is carried out using regression methods, correlation, discriminant analysis, artificial neural networks, genetic algorithms and other methods;

– today there is no systematic approach to the development of diagnostic methods in which a gas pumping unit with an automatic control system is considered as a single dynamic system, the components of which are both mechanical components and parts, as well as automatic control and automation systems. Therefore, when developing a method for diagnosing a specific component of this system, it is necessary to take into account the influence of its other components on the diagnosis result;

– much less attention was paid to the development of methods for monitoring the efficiency and diagnosis of the automatic control system of a gas pumping unit. This can be explained by the complex and little studied nature of the interaction of the automatic control unit of the gas pumping unit with individual components of the gas pumping unit in the event of both their failures and the automatic control system and automation.

At the same time, the solution to this problem can be based on parametric identification methods. They provide for assessing the state of a dynamic system, which is a gas pumping unit with an automatic control system based on an analysis of its transient process with a certain typical input action and finding the transfer function parameters of the main control valve circuits.

3. The aim and objectives of research

The aim of research is to develop a method for monitoring the operability of the automatic control system of a gas pumping unit in operation during its acceleration characteristics by finding the parameters of the transfer function of the main control circuits of the gas pumping unit and, on this basis, calculating the areas formed by the normalized transient response and the abscissa axis.

To achieve the aim, the following objectives are set:

– on the basis of experimental studies of the operation of the gas pumping unit in transient conditions, develop a method for monitoring the efficiency of the automatic control system of the gas pumping unit;

– to develop a methodology for processing the experimental results in the form of acceleration characteristics to obtain normalized transfer functions;

– to test methods for monitoring the performance of the automatic control system of the gas pumping unit and formulate recommendations for their further use.

4. The method of monitoring the performance of the automatic control system of gas pumping units with their accelerating characteristics.

Experimental studies have shown that the dynamic characteristics of a gas pumping unit (GPU) of natural gas are aperiodic in various transmission channels of input influences and, in general, their transfer functions are [20]:

$$W(s) = k \frac{1 + \sum_{j=1}^{m} b_j s^j}{1 + \sum_{i=1}^{n} a_i s^i}, \qquad (1)$$

where k – object transfer coefficient; $a_i,\ i = \overline{1,n},\ b_j,\ j = \overline{1,m}$ – constant values – transmission function parameters (1).

In expression (1), the inequality always holds $m<n$.

Instead of the transfer function (1), let's consider its normalized transfer function

$$w(s) = \frac{1 + \sum_{j=1}^{m} b_j s^j}{1 + \sum_{i=1}^{n} a_i s^i}, \qquad (2)$$

for which $k=1$.

In experimental studies, the initial value of the object (GPU) $Y(t)$ is a dimensional quantity.

To obtain a normalized transient response, the initial value $Y(t)$ is represented in relative units

$$y(t_k) = \frac{Y(t_k)}{Y_{\max}}, \quad k = \overline{1,N}, \qquad (3)$$

where $Y_{\max}$ output value $Y(t_k)$ in an experimental study at $t=t_N$; N – power array experimental research.

Since the accelerating characteristics of an object are aperiodic in nature, the poles $s_i\ i = \overline{1,n}$ of the normalized transfer functions (2) are placed in the left half-plane of the complex root plane. Let's assume that among the poles $s_i\ i = \overline{1,n}$ there are no multiple.

The quantity $y(t)$ can be found from the transfer function (2) provided that the input quantity $x(t)=1(t)$. In this case $\lim_{t \to \infty} y(t) = 1$.

Then the image of the output quantity $y(t)$ according to Laplace will be:

$$Y(s) = \frac{w(s)}{s}.$$

In accordance with the surplus theorem [25], according to the well-known transfer function (2), when $X(s) = \frac{1}{s}$, it is possible to find the normalized transition characteristic by the following formula:

$$y(t) = \sum_{i=0}^{n} \lim_{t \to s_i} (s - s_i) Y(s) e^{st}.$$

Since $Y(s)$ has one zero root, then

$$y(t) = 1 + \sum_{i=1}^{n} \lim_{t \to s_i} (s - s_i) Y(s) e^{st}.$$

Taking into account that the denominator of the function $w(s)$ is a polynomial of degree n, let's represent the function $Y(s)$ in this form:

$$Y(s) = \frac{1 + \sum_{j=1}^{m} b_j s^j}{s \left(1 + \sum_{i=1}^{n} a_i s^i\right)}, \qquad (4)$$

The expression $1+\sum_{i=1}^{n}a_i s^i$ is decomposed into prime factors. Then

$$Y(s)=\frac{1+\sum_{j=1}^{m}b_j s^j}{a_n s\prod_{i=1}^{n}(s-s_i)}.$$

Taking into account the last expression, formula (4) takes the following form:

$$y(t)=1+\frac{1}{a_n}\sum_{k=1}^{n}B_k\frac{e^{s_k t}}{s_k}\prod_{\substack{i=1\\i\neq k}}^{n}\frac{1}{s_k-s_i}, \qquad (5)$$

where $B_k=1+\sum_{j=1}^{m}b_j s_k^j$; s_i, s_k – function poles $Y(s)$.

The technical condition of the automatic control system of the gas pumping unit will be evaluated by changing the area S, which is formed by the transition characteristic (5). Obviously, at the $t\to\infty$ area S will also tend to infinity. Therefore, let's choose the finite time t_f in the calculus S from the condition $y(t_f)=y_f$. Let's find the value of t_f by solving the equation and obtain from the relation (5)

$$\sum_{k=1}^{n}B_k\frac{e^{s_k t_f}}{s_k}\prod_{\substack{i=1,\\i\neq k}}^{n}\frac{1}{s_k-s_i}=a_n(y_f-1), \qquad (6)$$

Equation (6) is non-linear with respect to t_f and the half-division method (dichotomy method), which contains a local root, is used to find its value [25].

Let's calculate the area S_f, by taking the integral from the right-hand side of equation (6), when t varies from 0 to t_f. So,

$$S_f=\int_0^{t_f}\left(1+\frac{1}{a_n}\sum_{k=1}^{n}B_k\frac{e^{s_k t}}{s_k}\prod_{\substack{i=1,\\i\neq k}}^{n}\frac{1}{s_k-s_i}\right)dt.$$

From the last expression let's find

$$S_f=t_f+\frac{1}{a_n}\sum_{k=1}^{n}\frac{B_k}{s_k^2}\left(e^{s_k t_f}-1\right)\prod_{\substack{i=1,\\i\neq k}}^{n}\frac{1}{s_k-s_i}. \qquad (7)$$

For the chosen value of t_f, formula (7) allows to determine the area S_f, created by the transition characteristic and the abscissa axis from the values of the poles of the transfer function.

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5. The results of experimental studies of the method for monitoring the performance of gas pumping units by accelerating characteristics

Experimental studies to verify the feasibility of evaluating the technical condition of the automatic control system of gas pumping units with their accelerating characteristics were carried out at the compressor station No. 39 "Bogorodchany" (Ukraine) for nine months.

The experimental research program provided for the recording of such technological parameters: rotor speed of a low-pressure turbine and a high-pressure turbine, hydraulic oil pressure, axial compressor pressure, and GPU exhaust temperature.

The change in the current values of these parameters during the GPA technological start-up was monitored using the GPU SAT-01 D automatic control system monitor and

recorded in the archive using regular means of the automatic control system with an interval of 0.1 second.

For further processing of trends of controlled parameters of the gas pumping unit, the data from the automatic control system were recorded in the form of .csv files (time stamp, parameter value), which were then converted into .xlsx files.

Monitoring of technological parameters was carried out during 2019 from March to December. Nine overclocking characteristics of the gas pumping unit were obtained in the coordinates "time-values of technological parameters".

As an example, Fig. 2 shows the GPU acceleration characteristic in the coordinates "time - frequency of rotation of a high-pressure turbine" recorded on 05/30/2019.

According to the acceleration characteristic, it is necessary to determine the structure of the transfer function and its parameters.

The accelerating characteristic of the GPU "time - frequency of rotation of the high-pressure turbine" will be described by the normalized transfer function (1).

Thus, it is necessary to determine the parameters of the transfer function and with the normalized transient response of the GPU y (t), the ordinates of which should be calculated by formula (3).

The structure of the transfer function and its parameters will be determined by the area method (the Simoiu method) [20, 26].
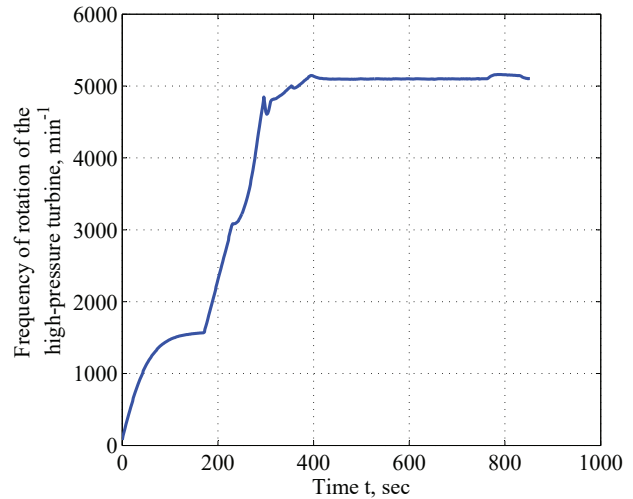

Fig. 2. GPU acceleration characteristic in coordinates "time - frequency of rotation of a high pressure turbine"

The idea of the area method is that the inverse transfer function $\tilde{w}(s)=\dfrac{1}{w(s)}$ expands in a Taylor series in a neighborhood of a point $s=0$. Moreover, in the function $w(p)$ artificially align the degrees of the polynomials of the numerator and denominator, assuming that $b_n=b_{n-1}=\cdots=b_{m+1}=0$. Then

$$\frac{1+\sum_{i=1}^{n}a_i s^i}{1+\sum_{j=1}^{n}b_j s^j}=1+S_1 s+S_2 s^2+S_3 s^3+\cdots.$$

Decomposition coefficients S_k have the content of areas of the k-th order [23]. It was proved [16] that between the values S_k and the parameters of the normalized transfer function (22) there is a functional relationship, having the form of a matrix equation

$$A\bar{\alpha} = \bar{S}, \tag{8}$$

where

$$A = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & \cdots & 0 & -1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 & \cdots & 0 & -S_1 & -1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 & \cdots & 0 & -S_2 & -S_1 & -1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 1 & \cdots & 0 & -S_{k-1} & -S_{k-2} & -S_{k-3} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 0 & \cdots & 0 & -S_{N-1} & -S_{N-2} & -S_{N-3} & \cdots & -1 \end{bmatrix},$$

$$\bar{\alpha} = \begin{bmatrix} a_1 \\ a_2 \\ \cdots \\ a_n \\ \hline b_1 \\ b_2 \\ \cdots \\ b_m \end{bmatrix}, \quad \bar{S} = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ \cdots \\ S_k \\ \cdots \\ S_N \end{bmatrix}.$$

To calculate values S_k an auxiliary function is introduced $\varphi(t) = 1 - y(t)$, which transformation according to Laplace will be such:

$$\Phi(s) = \frac{1}{s}\big(1 - w(s)\big).$$

Function decomposition $\Phi(p)$ in a Taylor series in a neighborhood of a point $p=0$, it gives such a result:

$$\Phi(p) = \mu_1 + \mu_2 s + \cdots + \mu_i s^{i-1} + \cdots = \sum_{i=1}^{\infty} \mu_i s^{i-1}, \tag{9}$$

where

$$\mu_i = \frac{1}{i!} \cdot \frac{d^i \Phi(s)}{ds^i}\bigg|_{p=0}.$$

In [16], it is shown that for known values μ_i values of quantities S_k can be determined from the matrix equation

$$\Lambda \bar{S} = \bar{\mu}, \tag{10}$$

where

$$\Lambda = \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 & 0 \\ -\mu_1 & 1 & 0 & 0 & \cdots & 0 & 0 \\ -\mu_2 & -\mu_1 & 1 & 0 & \cdots & 0 & 0 \\ -\mu_3 & -\mu_2 & -\mu_1 & 1 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ -\mu_{N-1} & -\mu_{N-2} & -\mu_{N-3} & -\mu_{N-4} & \cdots & -\mu_1 & 1 \end{bmatrix},$$

$$\bar{S} = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ \cdots \\ S_N \end{bmatrix}, \quad \bar{\mu} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \cdots \\ \mu_N \end{bmatrix}.$$

The value of S_1 is equal to the area formed by the auxiliary function $\varphi(t)$ and the abscissa

$$S_1 = \mu_1 = \int_0^{t_N} \varphi(t)\,dt.$$

Other values μ_i, $i = \overline{2,N}$, calculated according to the following formula:

$$\mu_i = S_i = \frac{1}{(i-1)!} \int_0^{t_N} (-t)^{i-1} \varphi(t)\,dt, \quad i = \overline{2,N}. \tag{11}$$

The technique for calculating areas S_i is described in [16].

Knowing the moments of the auxiliary function, from equation (10) let's determine the area

$$\bar{S} = \Lambda^{-1}\bar{\mu}. \tag{12}$$

After the areas are determined S_i, $i = \overline{1,N}$, with equation (8) let's define the parameters a_i, $i = \overline{1,n}$ та b_j, $j = \overline{1,m}$ of transfer function (2)

$$\bar{\alpha} = A^{-1}\bar{S}. \tag{13}$$

Software has been developed to implement the method for monitoring the operability of the automatic control system of the gas pumping unit according to the values of the acceleration characteristics in the MatLab environment. Such software makes it possible to determine the parameters of the transfer function from the experimental curve of the object and the size of the area limited by the transition function $y(t)$ of the object.

The task software consists of two software products.

The first of them allows to translate the present time, which is recorded in the database of the automatic control system in the format "date-month-year", "year-minute-second", in the time interval from the moment of observation to its end in seconds (minutes).

The second software product consists of the main program (Script-file) and subprograms (M-files). The software has the following routines:

1. Area calculation S_i, $i = \overline{1,N}$.

2. Calculation of the moments of functions by the formula (10), where $i = \overline{1,N}$.

3. Matrix formation A.

4. Visualization of software results.

5. Time calculation t_f. Since equation (6) is nonlinear with respect to the sought quantity t_f, then to solve it, the dichotomy method is used [22].

6. Area calculation S_f according to the formula (7).

The second software product provides an interactive mode of work with the researcher, when the latter introduces the order of the polynomial of the numerator m and the order of the polynomial of the denominator n. In this case, the relation $m \leq n$.

Information on the value of the parameters of the transfer function contains the vector $\bar{\alpha}$, first n which components are parameters a_i, and the last $N-n$ components are parameters b_j.

As an example, Fig. 3 shows the normalized transient response of a gas pumping unit in the coordinates "time-frequency of rotation of a high-pressure turbine" (Fig. 3).

The polynomial order of the numerator of the transfer function (2) were chosen $m=1$ and accordingly, the polynomial order of the denominator $n=2$.

With the help of the developed software product, the input data for which the overclocking characteristic was ex-

perimentally obtained, in the dialogue mode of the program, the normalized transfer function is obtained

$$w(s) = \frac{b_1 s + 1}{a_2 s^2 + a_1 s + 1},$$

where $a_1 = 198.1189\,c$, $a_2 = 14{,}011.6064\,c^2$; $b_1 = 13.8991\,c$.
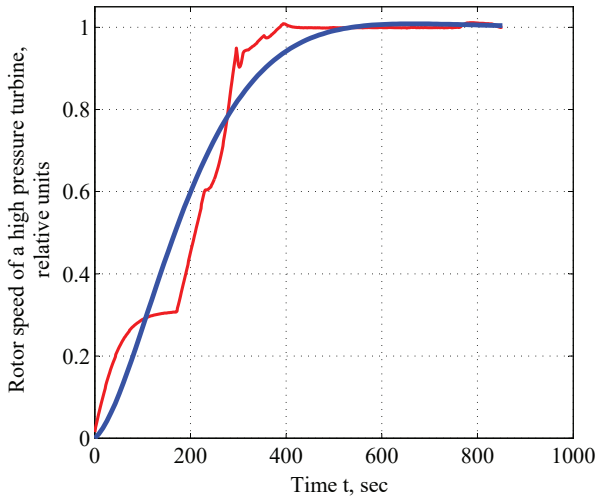

Fig. 3. GPU acceleration characteristic in coordinates "time - rotational speed of a high-pressure turbine rotor" and its approximation

Using the developed software for nine overclocking characteristics, the normalized transfer functions and their parameters were determined. The calculation results are reflected in Table 2.

The analysis of Table 2 shows that over time, the structure and parameters of the GPU transfer function change in the coordinates "time is the rotational speed of the rotor of the high pressure turbine", which may be a consequence of a change in the technical condition of the automatic control system of gas pumping unit.

The technical condition of the automatic control system of the gas pumping unit will be evaluated by the value of the area S_f, which was calculated by the formula (6). To identify a trend in changing values S_f it is necessary to ensure the calculation of values S_f under identical conditions. This is achieved by choosing such a finite time t_f under which the condition $-\,y(t_f) = y_f$. Value has been established $y_f = 0.98$.

According to the formula (6) using the developed software for transfer functions, the structure and parameters of which are reflected in Table 1, values S_f were calculated, which are listed in Table 3.

To identify trends S_f plotted in time in coordinates $S_f - t$ (Fig. 4), which shows that over time there has been an increase in area values S_f.
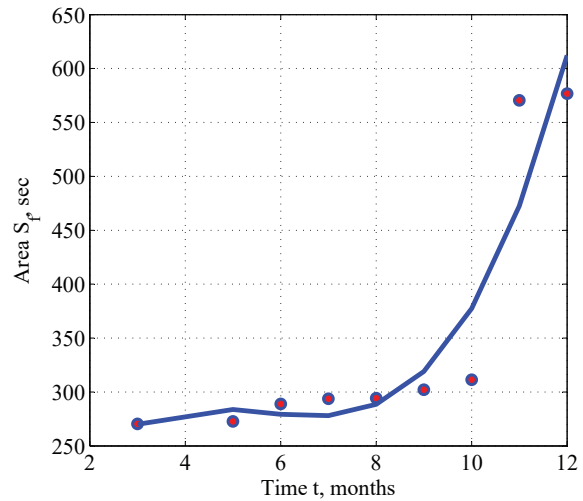

Fig. 4. Change of values S_f in time

The experimental data (Fig. 4) are described by an empirical model, which choose in the form of a polynomial of the third degree

$$S_f(t) = \pi_0 + \pi_1 t + \pi_2 t^2 + \pi_3 t^3. \tag{14}$$

Table 2

The structure and parameters of the normalized transfer function of the gas pumping unit in the coordinates "time - frequency of rotation of the high-pressure turbine"

No.	Month	Numerator polynomial order, m	Denominator polynomial order, n	Parameters of the normalized transfer function
1	March	1	2	$a_1 = 201.3810\,c$, $a_2 = 13{,}619.5628\,c^2$; $b_1 = 10.2521\,c$
2	May	1	2	$a_1 = 198.1189\,c$, $a_2 = 14{,}011.6064\,c^2$; $b_1 = 13.8991\,c$
3	June	1	2	$a_1 = 190.0050\,c$, $a_2 = 12{,}304.2822\,c^2$; $b_1 = 10.3698\,c$
4	July	1	2	$a_1 = 186.2889\,c$, $a_2 = 12{,}076.0088\,c^2$; $b_1 = 6.4597\,c$
5	August	1	2	$a_1 = 184.3797\,c$, $a_2 = 11{,}943.2961\,c^2$; $b_1 = 6.1001\,c$
6	September	1	2	$a_1 = 178.70574\,c$, $a_2 = 11{,}166.1896\,c^2$; $b_1 = 2{,}8821\,c$
7	October	1	2	$a_1 = 479.8242\,c$, $a_2 = 79{,}952.1950\,c^2$; $b_1 = 68.8620\,c$
8	November	0	1	$a_1 = 185.4506\,c$
9	December	0	1	$a_1 = 182.5458\,c$

Table 3

Area values S_f in function of time t

Months	03	05	06	07	08	09	10	11	12
S_f	302.04	288.87	294.33	293.66	270.32	272.73	311.32	576.80	570.45

To determine the parameters of the empirical model (14), let's use the least squares method. So

$$\overline{\pi} = \left(F^T F \right)^{-1} F^T \overline{S}_f,$$

where

$$\overline{\pi} = \begin{bmatrix} \pi_0 \\ \pi_1 \\ \pi_2 \\ \pi_3 \end{bmatrix}$$

– model parameter vector (14);

$$F = \begin{bmatrix} 1 & t_1 & t_1^2 & t_1^3 \\ 1 & t_2 & t_2^2 & t_2^3 \\ \dots & \dots & \dots & \dots \\ 1 & t_9 & t_9^2 & t_9^3 \end{bmatrix}; \quad \overline{S}_f = \begin{bmatrix} S_f^{(1)} \\ S_f^{(2)} \\ \dots \\ S_f^{(9)} \end{bmatrix}$$

– value vector $S_f^{(i)}$, $i = \overline{1.9}$ (Table 2).

The following values of the parameters of the empirical model were obtained (14): $\pi_0=68.08$, $\pi_1=124.17$, $\pi_2-23,09$, $\pi_3=-1.38$.

The dependence graph (14) is plotted in Fig. 4, which shows that the value S_f to $t \le 10$ months remains virtually unchanged; then rises sharply to a value 570.45, which indicates a deterioration in the technical condition of the automatic control system of GPU.

6. Discussion of the results of the study on the possibilities of the method of monitoring the efficiency of the automatic control system of gas pumping unit

During operation of the automatic control system of the gas pumping units, their aging occurs, which in turn is manifested in a deterioration in the quality of the process of controlling gas pumping units. Such a deterioration of the control process adversely affects the technical condition of the gas pumping unit and is manifested through overclocking characteristics through the corresponding signal transmission channels (Table 2).

Compared with the known methods in which the efficiency of the automatic control system of a gas pumping unit is controlled by changing the parameters of the transfer functions, this paper was the first to propose an integral criterion (7) for assessing the efficiency of the automatic control system of a gas pumping unit, which largely eliminates the subjective factor in calculating the parameters of the transfer function.

In addition, the integral criterion (7) is less sensitive to interference that is superimposed on the overclocking characteristics of the automatic control system of the gas pumping unit, obtained during its operation, through the corresponding input impact transmission channels.

The use of the proposed method is possible only when it is possible to obtain overclocking characteristics of the automatic control system of the gas pumping unit during its operation for a long time.

Since the automatic control system of the gas pumping unit and the control object (gas control unit) is the only system and the elements of this system are in constant interaction, the problem of identifying failures of both the object itself and the automatic control system arises. Further research by the authors will be directed toward solving this scientific problem.

7. Conclusions

1. A technique has been developed to obtain the acceleration characteristics of the automatic control system of the gas pumping unit for input actions in the start-up mode of the gas pumping unit, which allows to obtain experimental data for constructing normalized transfer functions of the gas pumping unit.

2. Based on the analysis of the obtained normalized transfer functions of the gas pumping unit, a substantiated method for assessing the efficiency of the automatic control system of the gas pumping unit, which, in contrast to the known parametric methods, is based on the determination of the areas of transition characteristics as diagnostic signs of the state of the automatic control system of the gas pumping unit.

3. The developed method was tested on experimental data obtained during nine technological launches of the GPU GTK-25-i according to the developed methodology, which confirmed its operability. Further implementation of the developed method requires determining the conditions of its operability and parallel monitoring of the technical condition of the mechanical units of the gas pumping unit in order to exclude their influence on the result of monitoring the state of the automatic control system of the gas pumping unit.

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