Проведені експериментальні дослідження динамічних властивостей газоперекачувальних агрегатів (ГПА) різних типів, які дозволили отримати криві розгону ГПА та визначити параметри функції передачі по різних каналах передачі вхідних впливів. Для цього було розроблено метод і програмний продукт для реалізації процедури визначення площ k-тих порядків через моменти допоміжної функції. У результаті проведених експериментів на діючих ГПА отримані розгінні характеристики за вибраними каналами передачі сигналів. Для ідентифікації динамічних властивостей ГПА розроблено програмний продукт у середовищі MatLab, який дозволяє в ітераційному режимі кожну криву розгону апроксимувати функцією передачі, порядок якої вибирається користувачем. Ітераційний режим дозволяє користувачу вибирати порядок поліномів чисельника і знаменника функції передачі, а також обчислювати числові значення параметрів вибраної функції передачі. Програмний продукт апробовано на промислових даних, отриманих при штатному пускові ГПА. Отримані результати можуть бути використані при розробці нового методу контролю надійності та діагностування технічного стану систем автоматичного управління (САУ) ГПА і його вузлів. Суть методу полягає в тому, що зміна технічного стану САУ чи ГПА впливає на їх динамічні властивості, а це, в свою чергу, викликає зміну параметрів функцій передачі, яка може бути зафіксована через певний проміжок часу. Визначивши діапазони зміни значень коефіцієнтів функції передачі для різних технічних станів різнотипних САУ і ГПА в подальшому можна буде прогнозувати період їх експлуатації

Ключові слова: газоперекачувальний агрегат, експериментальні дослідження, розгінна характеристика, метод площ, технічний стан, програмний продукт, функції передачі

EVALUATION OF DYNAMIC PROPERTIES OF GAS PUMPING UNITS ACCORDING TO THE RESULTS OF EXPERIMENTAL RESEARCHES

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1. Introduction

Gas pumping units (GPU) is a key element of the entire gas transmission system (GTS). The role of monitoring, control, diagnostics and protection of the GPU is assigned to the automatic control system (ACS). The development of integrated automation tools, a reduction in the number of service personnel, and more complex operating conditions for equipment require high reliability of operation of both new and those GPU that are in operation [1, 2]. In the context of a significant number of GPU in the composition of the GTS, the relevance of assessing the technical condition of elements of GPU ACS does not cause questions. Such an estimate can be obtained using mathematical modeling of elements of control systems.

Modern automatic control systems are being developed as computer-integrated systems that put forward qualitatively new requirements for mathematical models of controlled ob-

jects [2]. It is impossible to ensure high reliability of the system diagnostics if an adequate diagnostic model of the object is not created. To build diagnostic models, you can use both theoretical and experimental methods.

Theoretical methods are based on the fundamental laws of nature, such as the conservation of energy and matter, the laws of physics, mechanics, heating, etc. A characteristic feature of such diagnostic models is that they are created in terms of "input-output". The creation of such models requires, on the one hand, a highly qualified scientist, and on the other, the resulting diagnostic model is not always adequate to a real object.

Therefore, in the process of designing control systems, experimental studies are carried out simultaneously with theoretical ones in order to create and refine models. Experimental methods of creating models have also an independent importance in cases where the object is rather complex or little studied. In this case, it is assumed that the structure of

the model and the class of models to which it can be attributed are known. Then the task of identification is to determine the unknown parameters, provided that the specified structure of the model is preset.

Development of methods for diagnosing and determining the technical state of GPU on the basis of creating mathematical models and analyzing changes in their parameters is an important scientific task.

2. Literature review and problem statement

To ensure reliable operation of the main equipment of the compressor station (CS), the methods for monitoring and identifying the main parameters of centrifugal superchargers (CS) are widely used, which make it possible to detect damage at the initial stage of their development and to assess the admissibility of further operation of the CS. In this regard, the importance of developing and improving identification methods is increasing, which allows us to construct their mathematical model based on the results of research on the properties of technological objects [3–6].

A significant number of scientific works are devoted to identification methods [3]. One of the first was the work [4, 5], in which the frequency identification methods were initiated according to the results of observations of harmonic signals of different frequencies at the input and output of the object. Such a method is unacceptable for the majority of industrial facilities, since the normal operation of the facility is disrupted, and a considerable amount of time is required to obtain high-quality experimental material. The authors of [7] propose to evaluate the change of the technical condition of the units by the values of the measured technological parameters of the GPU and by the characteristics of the GPU, such as noise, vibration, color of exhaust gases, air leakage along the path and, in particular, by regenerators and etc.

In [6, 8], the authors describe a new method for finding damage based on the identification of system complexity. In general, the complexity of a system is defined as the amount of information that needs to be described.

The advantage of this method is the ability to obtain holistic information about the state of the system by processing a significant array of data. The effectiveness of this method is confirmed by the performed studies, however, the error of this method is not indicated, as well as the effect of each measuring signal on the total measured complexity.

The effectiveness of parametric identification methods is determined not only by the quality of functional algorithms, but also by the quality of technical means. The authors of [9] emphasize that to determine the performance losses of centrifugal superchargers, it is necessary to take account of the errors of the measuring equipment, analyze the gas composition and collect data under stable conditions of the compressor operation (when the inlet and outlet temperatures do not change by more than 1 °C for 3-5 minutes).

The authors of the article [10] investigated the relationship between the main parameters of the centrifugal superchargers and its vibration signals by performing a series of experiments on experimental installation. The results of all tests showed that the vibration level increases with increasing flow rate and the presence of a corresponding defect, but to identify damage it is necessary to do a lot of research.

The combination of several methods allows you to identify effectively the parameters of the supercharger. In particular,

the use of a genetic algorithm in combination with the wavelet transform and the neural network provides the method with structural stability, global search and high speed [11].

Correlation methods are used [12] in the case when the experimental data are obtained as a result of observations of an object operated in a normal mode. In this case, the input of the object must be given a signal close to white noise, which is not always possible [13].

Regression methods can be applied in the case when the object model is represented in the state space [12, 13], which greatly complicates the identification process. In addition, it is assumed that the disturbances that act on the object are additive and in their properties are white noise. Such an assumption too idealizes real objects. Therefore, such methods have more theoretical value than practical.

The identification of an object by acceleration characteristics is widespread among the active methods. For objects whose dynamics are described by differential equations not higher than the second order, the parameters of the model are determined directly from the acceleration characteristic [14]. This method of determining the parameters of the model can be successfully applied in cases where the object is under the influence of minor noise.

Recently, more and more attention has been attracted to the method called the "area method" [14]. In [15], based on the area method, a method was modified in which the degrees of the polynomials of the numerator and denominator of the transfer function are positive fractional numbers. This form of the transfer function makes it difficult to interpret the results of identification and the need arises to introduce such a concept as fractional differentiation [16].

The analysis of literary sources showed that there are a number of scientific problems that need to be further solved:

– the possibility of obtaining high-quality experimental data when the desired test signals are applied to an object of study;

– the difficulty of obtaining mathematical models by the analytical method and their inconvenience for practical use;

– taking into account the effects of interference;

– selection and implementation of numerical methods for identifying objects.

3. The aim and objectives of the study

The aim of the work is to estimate the dynamic properties of GPU by experimentally taken accelerating characteristics by finding the parameters of the transfer function of the main control loops of the GPU using the area method. Determining the parameters of the transmission functions for different control loops for the GPU with different technical conditions (or operating time) will make it possible to establish the operating conditions for the elements of the GPU ACS and to formulate recommendations for their further operation.

To achieve this goal, it is necessary to perform the following tasks:

– to develop a methodology for diagnosing the technical state of GPU automation systems and its structural units based on the use of the method of Sima and the software for its implementation;

– to develop a program for conducting experimental studies on the diagnosis of the technical state of GPU automation systems;

– to process the obtained experimental data using the proposed method.

4. Theoretical principles of the area method. Numerical solution method

It is assumed that at a small value of the input effect on the object, the relationship between the input and output of the object is described by a linear differential equation with zero initial conditions, which in the Laplace image area will be represented by the transfer function

$$W(p) = k \frac{b_m p^m + b_{m-1} p^{m-1} + \cdots + b_1 p + 1}{a_n p^n + a_{n-1} p^{n-1} + \cdots + a_1 p + 1}, \tag{1}$$

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

For real objects, the relation $m \le n$ always holds.

By the form of the acceleration curve of the object, the value of m and n could be estimated. Once the order of the object transfer function is selected, the question of determining the parameters a_i, $i = \overline{1,n}$ and b_j, $j = \overline{1,m}$ on the experimentally taken acceleration curve of the object arises.

We will consider an object with self-leveling, which, with a single discontinuous input action, will be characterized by a transition characteristic $H(t)$. We assume that at time t_0, which is the origin of observations, $H(t_0)=0$. If at time instant $H(t_0)$ is nonzero, then by appropriate transfer of coordinates it is easy to attain the condition $H(t_0)=0$.

We turn from the characteristic $H(t)$ of the object to its normalized characteristic. To do this, expression (1) is presented in the following form:

$$\frac{W(p)}{k} = \frac{b_m p^m + b_{m-1} p^{m-1} + \cdots + b_1 p + 1}{a_n p^n + a_{n-1} p^{n-1} + \cdots + a_1 p + 1}. \tag{2}$$

The normalized transfer function $w(p)=W(p)/k$ will correspond to the time characteristic of the object $h(t)$. Let us find its value as $t\to\infty$, when a single hopping signal $1(t)$ is fed to the input. So:

$$\lim_{t \to \infty} h(t) = \lim_{p \to 0} p w(p) \cdot \frac{1}{p} = 1.$$

The characteristic $h(t)$, for which its ordinate goes to unity as $t\to\infty$, is called the normalized characteristic [17].

Thus, it is necessary to determine the parameters of the transfer function $w(t)$: a_i, $i = \overline{1,n}$ and b_j, $j = \overline{1,m}$, according to the normalized transition characteristic of the object $h(t)$.

To obtain the characteristic $h(t)$ it is necessary to divide all the values of $H(t)$ by the steady-state value H_{init} of the initial value of the object.

$$h(t) = \frac{H(t)}{H_{init}}.$$

The idea of the area method is that the inverse transfer function $\hat{w}(p)=1/w(p)$ is decomposed into a Taylor series of the point p = 0. Moreover, in the function $w(p)$, the degrees of the polynomials of the numerator and the denominator are artificially aligned, assuming that $b_n=b_{n-1}=...=b_{m+1}=0$. Then

$$w(p) = \frac{b_n p^n + b_{n-1} p^{n-1} + \cdots + b_1 p + 1}{a_n p^n + a_{n-1} p^{n-1} + \cdots + a_1 p + 1}. \tag{3}$$

After the expansion of the function $\hat{w}(p)$ in a Taylor series of the point p = 0, we will get

$$\frac{a_n p^n + a_{n-1} p^{n-1} + \cdots + a_1 p + 1}{b_n p^n + b_{n-1} p^{n-1} + \cdots + b_1 p + 1} = 1 + S_1 p + S_2 p^2 + S_3 p^3 + \cdots.$$

Given the ratio (3), we will have

$$\frac{1}{w(p)} = 1 + S_1 p + S_2 p^2 + S_3 p^3 + \cdots. \tag{4}$$

The coefficients of the expansion of S_k in the formula (4) h ave the content of areas of the k order [18] and can be calculated by the formula:

$$S_k = \underbrace{\int_0^\infty \int_0^t \cdots \int_0^t}_{k} \left(z_k(\tau) - z(\tau) \right) \underbrace{d\tau d\tau \ldots d\tau}_{k}, \quad k = 1, 2, \ldots. \tag{5}$$

The values of $z(t)$ and $z_k(t)$ correspond to the transfer function:

$$\frac{1}{W_z(p)} = 1 + \sum_{i=1}^{\infty} a_i p^i; \quad W_{z_k}(p) = \frac{1}{1 + \sum_{i=1}^{k} a_i p^i}.$$

From equation (4), it is easy to determine the relationship between the parameters of the transfer function (3) and the areas S_k. The ratio (4) can be written in the following form:

$$a_n p^n + a_{n-1} p^{n-1} + \cdots + a_1 p + 1 =$$
$$= \left(1 + S_1 p + S_2 p^2 + S_3 p^3 + \cdots\right)\left(b_n p^n + b_{n-1} p^{n-1} + \cdots + b_1 p + 1\right).$$

Opening the brackets and equating the coefficients with the same degrees, we will get

$$a_k = \sum_{i=1}^{k-1} b_i S_{k-i} + b_k + S_k, \quad k = 1, 2, \ldots. \tag{6}$$

Equations (6) form a linear algebraic system in which the quantities a_i, $i = \overline{1,n}$ and b_j, $j = \overline{1,m}$ are unknown. The size of such a system is $m+n$.

Thus, if areas S_k, $k = \overline{1, m+n}$, are known, then from the system of equations (6) you can determine the parameters a_i, $i = \overline{1,n}$ and b_j, $j = \overline{1,m}$ of transfer functions (3).

The system of equations (6) is conveniently presented in a matrix-vector form. To do this, we rewrite the system of equations (6) in expanded form:

$$a_1 - b_1 = S_1,$$
$$a_2 - b_1 S_1 - b_2 = S_2,$$
$$a_3 - b_1 S_2 - b_2 S_1 - b_3 = S_3,$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{7}$$
$$a_k - b_1 S_{k-1} - b_2 S_{k-2} - \cdots - b_{k-2} S_2 - b_{k-1} S_1 - b_k = S_k,$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$a_N - b_1 S_{N-1} - b_2 S_{N-2} - \cdots - b_{N-2} S_2 - b_{N-1} S_1 - b_N = S_N,$$

where $N=m+n$.

Turning to the matrix-vector form of writing the system of equations (7), we will get

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

where

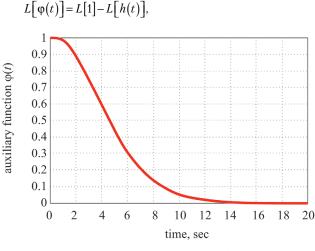$$A = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & \cdots & 0 & -1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 & \cdots & 0 & -S_1 & -1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 & \cdots & 0 & -S_2 & -S_1 & -1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots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

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

In matrix A, you can select a single submatrix of size $n \times n$. Under it, a zero submatrix of size $m \times n$ will be placed. It is convenient to fill the rest of the matrix with columns. The first element $n+1$ column «−1», the second element $n+1$ column «−S_1», the third − «−S_2», fourth − «−S_3» etc. $n+1$ column ends with the «−S_{N-1}» element. The following columns are filled with a zero offset down one element in the previous column of the matrix. To solve the matrix-vector equation (8) it is necessary to determine the area S_k, $k = \overline{1,N}$. Formula (5) is unsuitable for practical use, since the calculation of the values S_k, $k = \overline{1,N}$ requires multiple integration. A more efficient method of S_k, $k = \overline{1,N}$ calculation is the method of moments [18], which does not require multiple integration.

Form the auxiliary function $\varphi(t)$ (Fig. 1) which is determined by the formula

$$\varphi(t) = 1 - h(t),$$

and transform it according to Laplace

$$L[\varphi(t)] = L[1] - L[h(t)],$$

Fig. 1. Auxiliary function $\varphi(t)$

insofar as $L[h(t)] = h(p)$.

On the other side $h(p) = w(p)/p$. If we take account of formula (3), we will get

$$\Phi(p) = \frac{1}{p}(1 - w(p)). \tag{9}$$

If the function $\Phi(p)$ is expanded into a Taylor series of the point $p=0$, then we arrive at the following result:

$$\Phi(p) = \mu_1 + \mu_2 p + \cdots + \mu_i p^{i-1} + \cdots = \sum_{i=1}^{\infty} \mu_i p^{i-1}, \tag{10}$$

where

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

by definition

$$\Phi(p) = \int_0^{\infty} \varphi(t) e^{-tp} dt.$$

Differentiating successively the last expression i-1 times by the variable p and equating p to zero, we obtain

$$\mu_i = \frac{1}{(i-1)!} \int_0^{\infty} (-t)^{i-1} \varphi(t) dt, \quad i = 1, 2, \ldots \tag{11}$$

Equation (9) is reduced to this form:

$$(1 - p\Phi(p)) \frac{1}{w(p)} = 1. \tag{12}$$

After substitution of the value $w(p)$ and $\Phi(p)$ from the formulas (4) and (10) to the formula (12), we come to this result

$$(1 - \mu_1 p - \mu_2 p^2 - \cdots - \mu_k p^k - \cdots) \times$$
$$\times (1 + S_1 p + S_2 p^2 + S_3 p^3 + \cdots + S_k p^k + \cdots) = 1.$$

Performing simple algebraic transformations, we will get

$$(S_1 - \mu_1) p + (S_2 - \mu_1 S_1 - \mu_2) p^2 +$$
$$+ (S_3 - \mu_1 S_2 - \mu_2 S_1 - \mu_3) p^3 + \cdots = 0.$$

In order for the left side of the last equation for arbitrary values of p to be zero, the coefficients at the corresponding powers of the polynomial are equated to zero. As a result, we will get

$$S_1 - \mu_1 = 0,$$

$$-\mu_1 S_1 + S_2 - \mu_2 = 0,$$

$$-\mu_1 S_2 - \mu_2 S_1 + S_3 - \mu_3 = 0.$$

Summarizing the result, it can be argued that

$$-\sum_{i=1}^{k-1} \mu_i S_{k-i} + S_k = \mu_k, \quad k = \overline{1,N}. \tag{13}$$

So, we have a system of linear algebraic equations of dimension N

$$S_1 = \mu_1,$$
$$-\mu_1 S_1 + S_2 = \mu_2,$$
$$-\mu_2 S_1 - \mu_1 S_2 + S_3 = \mu_3,$$
$$-\mu_3 S_1 - \mu_2 S_2 - \mu_3 S_1 + S_3 = \mu_3,$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots,$$
$$-\mu_{N-1} S_1 - \mu_{N-2} S_2 - \mu_{N-3} S_3 - \cdots - \mu_1 S_{N-1} + S_N = \mu_N,$$

which we represent in the matrix-vector form

$$\Lambda \bar{S} = \bar{\mu}, \tag{14}$$

where

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

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

Since Λ is a lower diagonal matrix of size $N \times N$, it is advisable to form it as follows: place the units on the main diagonal ($\lambda_{ii} = 1$, $i = \overline{1,N}$); then under the main diagonal there will be elements $\lambda(i+k, j) = \mu(i-1)$, $i = \overline{2, N}$; $j = \overline{1, N-i+1}$; $k = \overline{0, N-1}$, while the outer cycle will be a cycle at index i. The index k is incremented by one inside the inner loop.

The expansion coefficients μ_i, $i = \overline{1,N}$, which are called the moments of the auxiliary function, are calculated by formula (11), replacing the infinite integration interval by the final observation time t_s, which introduces a certain error in calculating the values μ_i, $i = \overline{1,N}$.

Since the function $\varphi(t)$ is specified in the form of a graphical dependence, in order to find the integrals, which are defined by expression (11), it is necessary to use the methods of numerical integration [19].

Numerical integration can be carried out using the formulas of rectangles, trapezoids and Simpson formula. The smallest integration error will be when using the Simpson formula, based on approximation of the function $\varphi(t)$ by the Lagrange polynomial. It is assumed that the interpolation points t_i are equidistant from each other. Often in practice, the value of t_i is calculated with different steps along the time axis t. Therefore, we will perform numerical integration for the case when the value of t_i is not equidistant along the time axis t.

Let the value of $\varphi(t)$ be determined at discrete instants of time t_i, $i = \overline{1,q}$, where q is the number of interpolation points. In addition $t_{i+1} - t_i = h_i$, where $h_i \neq const$.

On the x-axis we will take three values $\tau_1 = t_i$, $\tau_2 = t_{i+1}$ and $\tau_3 = t_{i+2}$ (Fig. 2). They will correspond to the values of the ordinates of the function $\varphi(t)$ $y_1 = \varphi(t_i)$, $y_2 = \varphi(t_{i+1})$ and $y_3 = \varphi(t_{i+2})$.

If t_i is an interpolation point on the x-axis, and $\varphi(t_i)$ is the value of the function $\varphi(t)$ at the interpolation points,

then the Lagrange interpolation polynomial is defined by the following formula [20]:

$$L(t) = \sum_{k=1}^{N_1} \varphi_k \frac{\prod_{i=1, i \neq k}^{N_1} (t - t_i)}{\prod_{i=1, i \neq k}^{N_1} (t_k - t_i)}, \tag{15}$$

where $\varphi_k = \varphi(t_k)$; N_1 – the number of interpolation points.

Construct an interpolation polynomial for three points $\tau_1 = t_i$, $\tau_2 = t_{i+1}$ and $\tau_3 = t_{i+2}$ in which the auxiliary function $\varphi(t)$ takes values $y_1 = \varphi(t_i)$, $y_2 = \varphi(t_{i+1})$ and $y_3 = \varphi(t_{i+2})$:

$$L(\tau) = y_1 \frac{(\tau - \tau_2)(\tau - \tau_3)}{(\tau_1 - \tau_2)(\tau_1 - \tau_3)} +$$
$$+ y_2 \frac{(\tau - \tau_1)(\tau - \tau_3)}{(\tau_2 - \tau_1)(\tau_2 - \tau_3)} + y_3 \frac{(\tau - \tau_1)(\tau - \tau_2)}{(\tau_3 - \tau_1)(\tau_3 - \tau_2)}.$$

Considering that $h_1 = \tau_2 - \tau_1$, $h_2 = \tau_3 - \tau_2$ and $h_1 + h_2 = \tau_3 - \tau_1$, we will get

$$L(\tau) = \frac{y_1}{h_1(h_1 + h_2)} \left(\tau^2 - (\tau_2 + \tau_3)\tau + \tau_2\tau_3 \right) -$$
$$- \frac{y_2}{h_1 h_2} \left(\tau^2 - (\tau_1 + \tau_3)\tau + \tau_1\tau_3 \right) +$$
$$+ \frac{y_3}{h_2(h_1 + h_2)} \left(\tau^2 - (\tau_1 + \tau_2)\tau + \tau_1\tau_2 \right).$$

We find the area s_i bounded by the curve $L(\tau)$ on the segment $\tau \in [\tau_1, \tau_3]$. So,

$$s_i = \int_{\tau_1}^{\tau_3} L(\tau) d\tau = \frac{y_1}{h_1(h_1 + h_2)} \left(\frac{z_3}{3} - (\tau_2 + \tau_3)\frac{z_2}{2} + \tau_2\tau_3 z_1 \right) -$$
$$- \frac{y_2}{h_1 h_2} \left(\frac{z_3}{3} - (\tau_1 + \tau_3)\frac{z_2}{2} + \tau_1\tau_3 z_1 \right) +$$
$$+ \frac{y_3}{h_2(h_1 + h_2)} \left(\frac{z_3}{3} - (\tau_1 + \tau_2)\frac{z_2}{3} + \tau_1\tau_2 z_1 \right), \tag{16}$$

where $z_1 = \tau_3 - \tau_1$; $z_2 = \tau_3^2 - \tau_1^2$; $z_3 = \tau_3^3 - \tau_1^3$.
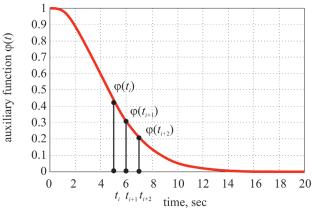

Fig. 2. Auxiliary function with selected interpolation points

Then the area μ_1, bounded by the curve $\varphi(t)$ will be equal to the sum of the areas s_i, each of which is calculated by the formula (16)

$$\frac{1}{i!}\int_0^{t_{N_1}}(-t)^i\varphi(t)\mathrm{d}t,$$

where R – the number of intervals of the duration of observations.

The moments μ_i of the functions were determined similarly.

$$\frac{1}{i!}\int_0^{t_{N_1}}(-t)^i\varphi(t)\mathrm{d}t,\quad i=\overline{1,N}.$$

In practice, the value of N rarely exceeds five. Therefore, knowing the moments of the auxiliary function, from the equation (14) we determine the area

$$\overline{S}=\Lambda^{-1}\overline{\mu}. \tag{17}$$

Once the areas S_i, $i=\overline{1,N}$ are determined, from the equation (8) determine the parameters a_i, $i=\overline{1,n}$, and b_j, $j=\overline{1,m}$ of the transfer function (1)

$$\overline{\alpha}=A^{-1}\overline{S}. \tag{18}$$

To visualize the results of the program, it is necessary to move from the transfer function to a system of differential equations in the form of Cauchy.

Let the object transfer function be known

$$W(p)=k\frac{b_np^n+b_{n-1}p^{n-1}+\cdots+b_1p+1}{a_np^n+a_{n-1}p^{n-1}+\cdots+a_1p+1}. \tag{19}$$

In the case when $m<n$ the part of the coefficients of the transfer function, which is in the numerator, is equal to zero: b_n, b_{n-1},..., b_{m+1}.

The transfer function (19) corresponds to such a system of differential equations [20]:

$$\frac{dx_1}{dt}=x_2+\beta_1u,$$

$$\frac{dx_2}{dt}=x_3+\beta_2u,$$

$$\frac{dx_{i-1}}{dt}=x_i+\beta_{i-1}u, \tag{20}$$

$$\ldots\ldots\ldots\ldots$$

$$\frac{dx_n}{dt}=-\frac{1}{a_n}\sum_{j=1}^n a_{j-1}x_j+\beta_nu,$$

$$y=x_1+\beta_0u,$$

where x_i, $i=\overline{1,n}$ – object state variables. The value of y corresponds to the output of the object with a single transmission coefficient. To obtain the initial value of the object, the dynamic properties of which are characterized by the transfer function (19) it is necessary to increase the value of y by a factor of k. Then $Y(t)=ky(t)$.

Unknown quantities β_i, $i=\overline{0,n}$ are found from such a system of linear algebraic equations:

$$\sum_{j=i}^n a_j\beta_{j-i}=b_i,\quad i=\overline{0,n}. \tag{21}$$

We present the system of equations (21) in a matrix-vector form

$$A_\beta\overline{\beta}=\overline{b}, \tag{22}$$

where

$$A_\beta=\begin{bmatrix}a_n & 0 & 0 & 0 & \cdots & 0\\ a_{n-1} & a_n & 0 & 0 & \cdots & 0\\ a_{n-2} & a_{n-1} & a_n & 0 & \cdots & 0\\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\ a_0 & a_1 & a_2 & a_{n-1} & \cdots & a_n\end{bmatrix},\begin{bmatrix}\beta_0\\ \beta_1\\ \beta_2\\ \\ \beta_n\end{bmatrix},\begin{bmatrix}b_n\\ b_{n-1}\\ b_{n-2}\\ \cdots\\ b_0\end{bmatrix}.$$

The vector of coefficients is found from (21). So,

$$\overline{\beta}=A_\beta^{-1}\overline{b}.$$

By known values β_i, $i=\overline{0,n}$ and input action $u(t)$, we solve a system of differential equations (20) with zero initial conditions numerically.

To implement the developed methodology, software has been developed that allows determining the parameters of the transfer function using the experimental curve of an object.

5. Results of experimental studies of the dynamics of gas pumping units

As an object of research, GPU type GTK-10-4 and GTN-10 were taken, mounted on the compressor station CS-2 "Dolyna" of the GTM "Prikarpattransgaz". Monitoring of the experiments was carried out using the interfaces of the GPU ACS and the interface of the automated workplace of the shift engineer CS-2. This made it possible to monitor the current values of the technological parameters on the monitors and to monitor the operative messages to the CS operator and the changes on the mnemonic diagrams and the recovery of the retrospective information. The program of experimental research envisaged the regular launch of the GPU type GTK-10. The launch of the GPU took place on April 5, 2018. The change in the current values of the technological parameters when the GPU was launched into operation in accordance with the program of experiments was monitored by the GPU ACS SAT-01 D monitor and recorded in the archive by the standard means of the ACS.

The gas turbine is controlled using software and hardware and GPU start-up schedules: a low-pressure turbine (LPT) speed controller, a high-pressure turbine regulator (HPT) and a temperature controller, and control using the Amot fuel consumption regulator.

According to the results of the experimental study, the accelerating characteristics of GPU were obtained through the channel "fuel gas consumption – rotor speed of the high-pressure turbine". Data are obtained at the start of the GPU. A fragment of the experimental results is given in Table 1. For data processing, a sample of which is presented in Table 1, a program that converts the time format "date. month.year", "hour.minute.second" into the time interval from the moment of observation to its end in seconds (minutes) was developed in MatLab environment.

Fig. 3 shows the result of the operation of the software for determining the dynamic properties of the channel "GPU inlet pressure – GPU outlet pressure". The following transfer function was selected:
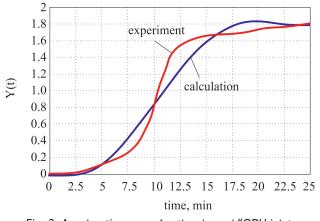
$$W(p)=\frac{k}{a_4p^4+a_3p^3+a_2p^2+a_1p+1}.$$

The result of the software operation are the following parameters of the transfer function: $k=1{,}77$; $a_1=10{,}36$; $a_2=47{,}64$; $a_3=125{,}03$; $a_4=192{,}36$.

Table 1

Fragment of data recording with standard information system equipment

Date	Time	Turns, min^{-1}
05.04.2018	12:59	0.0
05.04.2018	13:02	12.0
05.04.2018	13:04	12.0
05.04.2018	13:06	24.0
05.04.2018	13:06	48.0
05.04.2018	13:06	78.0
05.04.2018	13:06	108.0
05.04.2018	13:06	144.0
05.04.2018	13:06	162.0
05.04.2018	13:06	192.0

Fig. 3. Acceleration curve for the channel "GPU inlet pressure —GPU outlet pressure" and its approximation

Fig. 4 shows the acceleration curve of GPU along the channel "fuel gas consumption – rotor speed of the high-pressure turbine". According to the obtained acceleration characteristic, the channel transfer function is obtained, which has the following form:

$$W(p)=k\frac{b_2 p^2+b_1 p+1}{a_4 p^4+a_3 p^3+a_2 p^2+a_1 p+1},$$

where $b_1=20{,}7$ s, $b_2=17377{,}3$ s^2; $a_1=292{,}1$ s, $a_2=35066{,}6$ s^2, $a_3=2037107{,}9$ s^3, $a_4=45022073{,}7$ s^4.

Fig. 5 shows the acceleration characteristic of the channel "fuel gas consumption – rotor speed of the low-pressure turbine", obtained experimentally when GPU starts up.

The acceleration characteristic was approximated by the following transfer function:

$$W(p)=k\frac{b_1 p+1}{a_2 p^2+a_1 p+1},$$

where $b_1=20{,}7$ s; $a_1=232{,}1$ s, $a_2=9766{,}8$ s^2.

To study the dynamic properties of the pressure transmission channel of the natural gas blower "inlet pressure – outlet pressure" in the GPU start-up mode, the pressure change at the GPU outlet was recorded. At the start of the

observations, the pressure at the blower outlet was 38.07 bar, and at the end of the observations, the pressure rose to 43.8 bar. So, the pressure increase was 5.71 bar. This change in pressure over time is shown in Fig. 6.
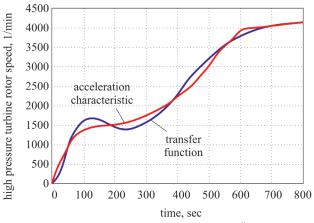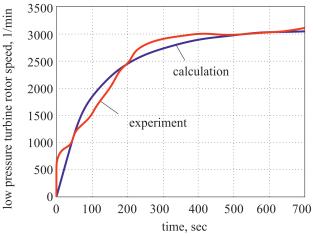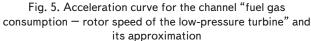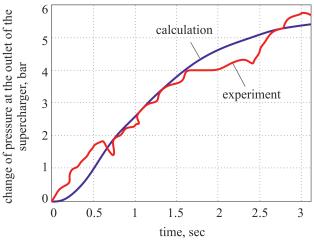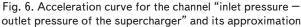

Fig. 4. Acceleration curve for the channel "fuel gas consumption — rotor speed of the high-pressure turbine" and its approximation

Fig. 5. Acceleration curve for the channel "fuel gas consumption — rotor speed of the low-pressure turbine" and its approximation

Fig. 6. Acceleration curve for the channel "inlet pressure — outlet pressure of the supercharger" and its approximation

With the help of the developed software, the obtained parameters of the transfer function were obtained

$$W(p) = \frac{k}{a_2 p^2 + a_1 p + 1},$$

where a_1=129954,5 s, a_2=4,3465×10^9 s^2.

Thus, as a result of experimental studies, the transfer functions of individual signal transmission channels were obtained, and their parameters were calculated using the developed software.

6. Discussion of the results of studies of the dynamic properties of GPU

To assess the technical condition of the GPU, it is necessary to form certain diagnostic features. The analysis of the literature and experimental studies have shown that dynamic characteristics change, when the technical state of the GPU changes. Such a change leads to a change in the parameters of the transfer functions of the corresponding signal transmission channels. This means that changing the parameters of the transfer functions of the GPU can be taken as diagnostic signs of the technical state of the GPU.

At the moment there are no analytical models on the basis of which one can obtain the corresponding transfer functions of the GPU. Therefore, a method and appropriate algorithmic support were developed, which allows us to determine the structure of the transfer functions, as well as its parameters, based on the obtained acceleration characteristics.

The determination of the parameters and structure of the transfer functions by the acceleration characteristics of the GPU is based on the area method.

The experimentally obtained acceleration characteristics during the start-up of GPU via signal transmission channels made it possible to determine the parameters of transfer functions with sufficient accuracy for practice.

The results obtained in the work can be used as the basis for a new method for diagnosing the state of an automatic control system for changing the type of transition curve based on direct quality indicators: overshoot, permissible number of oscillations and time of transition.

To do this, with the introduction of the GPU ACS in operation, or after repair work, they remove the acceleration curve of the GPU, which determines the transfer function coefficients, which will correspond to the nominal (operational) state of the ACS. During the operation of the GPU, after certain periods of time, they remove the acceleration curve and compare the obtained values of the transfer function coefficients with their nominal values, which will allow establishing the presence of changes in the technical condition of the ACS or the GPU itself. If there is a change in the technical state of the GPU ACS, the reasons for this change (search for a defect) are determined. The basis of any method of diagnosis lies in the working conditions according to the selected diagnostic features. In order to form the working conditions according to the criteria considered in the article, it is necessary to collect statistical data for each type of control system and with different operating time periods. On the basis of certain working conditions, it will be possible to predict the period of further trouble-free operation of the ACS and the GPU.

7. Conclusions

1. To study the coefficients of the transfer functions of the main control circuits of the GPU, a method is developed which is based on the procedure for determining the areas of the k orders through the moments of the auxiliary function, which allows determining both the parameters and the structure of the transfer function.

2. In the MatLab environment, an original software product is developed with which the orders of polynomials of the numerator and denominator of the transfer function can be selected in interactive mode and its parameters can be determined.

3. The method of identification of dynamic properties of the GPU was tested on industrial data obtained during normal start-up of the GPU, which confirmed its effectiveness. The results obtained in the work can be taken as the basis for the development of a method for monitoring the reliability and diagnostics of the GPU ACS.

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