TRENDS IN THE DEVELOPMENT OF METHODS FOR DIAGNOSTICS OF THE TECHNICAL STATE OF THE BLADES OF GAS-PUMPING UNITS

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ABSTRACT

Object of research: degradation processes occurring in the blades of a gas-pumping unit (GPU) during its long-term operation and cause the appearance of defects that lead to a change in their technical condition and breakage of the working blades and, as a result, to accidents.

Solved problem: obtaining a method for diagnosing the GPU blades, which can be used to determine its technical condition during the GPU operation.

The main scientific results: a classification of methods for diagnosing the GPU blades and their analysis was developed, according to the results of which it was established that the improvement of a new method of aerodynamic calculation of profiles relative to the GPU blades by developing mathematical models of the deformation process and flow around the GPU blades and calculation formulas for assessing their aerodynamic characteristics, will allow to simulate possible options for changing the technical state of the blades (the amount of wear of the blades, their number, deformation, etc.), to study their influence on the parameters of the oscillatory processes of the blades and to compile a dictionary (base) of diagnostic signs of their state. The use of such a base will make it possible to quickly determine the technical condition of the blades during the GPU operation and prevent the occurrence of emergency situations

The area of practical use of the research results: the enterprises of the gas transmission system, which operate GPU with a gas turbine drive

An innovative technological product: a method of direct aerodynamic calculation of airfoils relative to GPU blades to determine their technical condition during operation.

Scope of application of the innovative technological product: gas-pumping units with a gas turbine drive with a capacity of 6.3 MW to 25.0 MW

1. Introduction

1. 1. The object of research

The object of research is the degradation processes occurring in blades of a gas pumping unit (GPU) during its long-term operation and cause the appearance of defects that lead to a change in their technical condition and breakage of the working blades and, as a consequence, to accidents.

1. 2. Problem description

Long-term operation of the gas transmission system of Ukraine (about 40 years) has led to the fact that more than 70 % of gas pumping units (GPU) with a gas turbine drive have almost exhausted their resource (100 thousand hours). At the same time, the resource of individual parts and assemblies is much less (for example, the assigned resource for the blades varies in the range of 18 to 80 thousand hours. The statistics of failures of the main parts of the GPU over a long period shows that the blades accounts for up to 40 % of all GPU failures.

To determine the technical condition of the blades, various methods of its diagnostics are used today both when the unit is stopped and during the GPU operation. The most promising are the methods for diagnosing the state of the blades during the GPU operation.

The main components of the GPU driven by gas turbine engines (GTE) (for example, the GPU-Ts-16S) include: LPC, HPC – low and high pressure compressors; CC – combustion chamber; HPT, LPT – high and low pressure turbines; S – supercharger; ST – supercharger turbine, and IGV – inlet guide vanes, which are equipped with blades. So, IGV has one stage with 44 blades, nine-stage LPC and ten-stage HPC have respectively 308 and 690 blades; single-stage LPT and HPT have 100 and 86 blades, respectively, and three-stage S has 186 blades. Therefore, the term "blades" of the GPU means the blades of all the above units of the GPU.

A detailed analysis of the causes and factors responsible for the occurrence of defects and failures of the GPU blades has shown that fatigue failures of blades, which are among the most common types of defects, are mainly due to the action of resonant vibrations; unit operation in surge mode; gas flow pulsations; replaceable thermal stresses arising during starts and stops of the unit; uneven temperature field behind the combustion chamber. A significant number of diagnostic methods are used to determine the technical condition of the GPU blades. Therefore, a significant number of publications have been devoted to solving the problem of diagnostics of the GPU blades, both in our country and abroad [1, 2]

Practice shows that the control of the technical condition of the GPU blades in operation is carried out by visual inspection of the blades using the methods of visual-optical control, magnetic particle diagnostics, color flaw detection, vortex-room method, acoustic emission method and ultrasonic testing.

These methods provide for the performance of work to monitor the technical condition of the blades on a stopped GPU and are rather laborious, which requires professional skills and responsibility from the technical personnel.

The above methods do not take into account the effect of dynamic loads acting on the blades during the GPU operation and at which they develop and develop defects. In this regard, the blade, in which its defective properties begin to appear under load, will not necessarily be recognized as defective when examined by the methods considered.

The most effective methods for diagnosing such defects are the methods of vibroacoustic diagnostics, due to the high information content of vibroacoustic processes accompanying the GPU operation, their organic connection with the dynamic processes of excitation and propagation of oscillations in the mechanisms and nodes of the GPU, as well as the possibility of automating the collection and processing of diagnostic information using modern means of microprocessor technology and the latest packages of applied software products [3, 4]. Moreover, any defect of any unit that is subjected to mechanical stress from the moving parts or the flow of pulsating gas is characterized by an individual "vibration portrait".

1. 3 Proposed solution to the problem

The main problem when using the methods of vibroacoustic diagnostics is the choice (development) of effective methods and algorithms for processing vibroacoustic signals in order to determine rational diagnostic signs of a defect in the GPU blades.

Thus, the presence of a significant number of methods for diagnosing the GPU blades, as well as various transformations that can be performed when processing vibroacoustic processes in order to identify diagnostic signs of the technical state of the blades, requires their classification. In this regard, the problem of analyzing the methods for diagnosing the technical state of the blades from the point of view of their use during operation is urgent.

The aim of research is the classification and analysis of methods for diagnosing the technical state of the blades during the GPU operation in terms of choosing the most effective method for further use.

2. Materials and methods

To solve the problem posed in the work, the materials of scientific research publications on this topic were used with their subsequent analysis in order to select the most effective method for diagnostics of the blades and its further use to determine its technical state during the GPU operation.

A preliminary analysis of the known methods for diagnosing the GPU blades showed that they can be classified into three groups (**Fig. 1**)

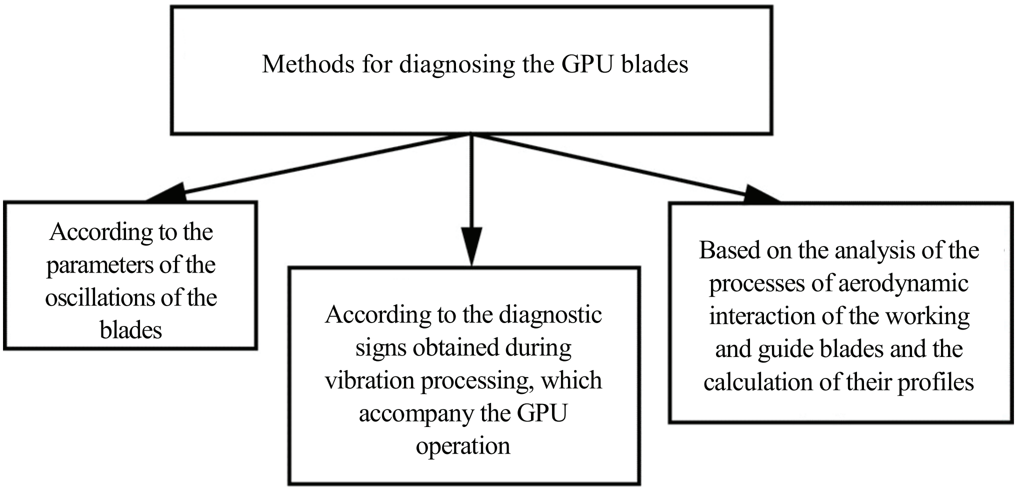

Fig. 1. Classification of methods for diagnosing the GPU blades

The first group includes methods for diagnosing a blade with natural frequencies of the blades, various modifications of the contactless discrete-phase method (DFM) and diagnosing self-oscillations (SO).

The composition of the methods of the second group is the most numerous in comparison with the methods of other groups. The methods are based on diagnostic features obtained during vibration processing that accompany the GPU operation, using various transformations: fast Fourier transform, discrete cosine transform, autocorrelation functions, distribution of Cohen's classes, S-transform, various wavelet transforms, etc.

The smallest number is the methods of the third group. They are based on the analysis of the processes of aerodynamic interaction of the working and guide blades and the direct aerodynamic calculation of the profiles relative to the GPU blades.

Let's consider in more detail the diagnostic methods for each of the above groups.

2. 1. Methods of diagnostics by the parameters of vibrations of the GPU blades

Application of the method of natural vibration frequencies for diagnostics of the working condition of blades is regulated by regulatory documents [5]. The values of the natural vibration frequencies of the blades for the most common units GTK-10-4 and GT-750-6 are given in [5] and it is proposed to issue an internal passport for each set of rotor blades in the manufacture of blades for each set of rotor blades, in which to enter the conclusion about the compliance of the natural frequencies of the blades with the normative ones. The method cannot be used during the GPU operation.

The non-contact discrete-phase method (DPM), which was developed in the 70s of the last century, consists in measuring the time intervals between the pulses of the root and peripheral sensors, comparing them with the geometric position of a particular blade in the wheel at certain points in time and the corresponding interpretation of the obtained values in the area mechanical stresses and deformations. The method makes it possible to determine the individual deformation state of each impeller blade of the GPU blades. This method is used nowadays when solving the problem of measuring the deformations of the rotor blades of a gas turbine engine, monitoring their state and registering the oscillations of the blades during transient modes of the GPU using this method [6, etc.]. The complexity of the technical implementation of this method does not allow its industrial use.

For the purpose of timely detection and prevention of fatigue destruction of compressor blades, self-oscillations (SO) are diagnosed in real time [7]. Despite a significant amount of research devoted to SO, algorithms and technical means for their reliable and timely diagnostics in real time are still not fully implemented. This is caused, first of all, by the difficulty of identifying diagnostic signs, which require a thorough analysis of already registered information.

2. 2. Methods based on diagnostic signs obtained during vibration processing that accompany the GPU operation

The method of vibration diagnostics of defects in gas turbine installations of ship DR59L and aircraft types NK-12ST with an output power of 10.4 MW and 6.3 MW, which was proposed by V. Startsev at the end of the 80s and has not lost its relevance, is based on two main provisions:

– an objective assessment of the state of the unit is possible by monitoring vibration at points, if possible, equidistant from the main sources of frame vibration;

– with a high probability, only developed defects can be detected, since the vibration signal, overwhelmed by incipient defects, practically dies out when passing through the selected control points.

The procedure for the implementation of the diagnostic technique is considered, which allows, in particular, to diagnose the wear of the impeller (wear of the blades), the cause of which is the wear of the end surfaces of the impeller blades and other defects. The technique is implemented in a software module for automated diagnostics of bearings and blades of two- and three-shaft gas turbines based on the DREAM for Windows package. The disadvantage in the implementation of the method lies in the difficulty of ensuring vibration control at points, if possible, equidistant from the main sources of frame vibration.

The work [8] is devoted to the determination of the technical state of GTE blades in the process of their functioning and the diagnosis of crack-like damage in them. For this, a dynamic model of a gas turbine engine was developed as an object of vibroacoustic diagnostics of crack-like damages of blades in stationary and non-stationary modes; regularities of the influence of damage on the parameters and characteristics of free and forced stationary and non-stationary oscillations of the blade models were established. The influence of damage on the correlation and spectral characteristics of the blade oscillations under unsteady narrow-band vibration excitation is analytically determined and investigated. Methods of multidimensional spectral analysis, time-frequency transformations, wavelet transformations and dimensionless amplitude characteristics of a vibroacoustic signal were used to process the diagnostic information obtained as a result of numerical and physical modeling of a GTE impeller in stationary and non-stationary modes of vibration disturbance. Based on the results of processing the diagnostic information, diagnostic signs of crack-like damage to the blades of gas turbines were identified and investigated, and methodological foundations for the use of neural networks for recognizing the technical condition of the blades in stationary and non-stationary modes were developed by quantitative signs and features in the form of contour images. However, the work does not provide the results of checking the adequacy of the developed models to the experimental data.

The use of bispectral analysis in the problems of vibroacoustic diagnostics of cracks in the blades of aircraft gas turbine engines in a stationary operation mode is considered in [1]. Simulation and processing of signals generated by a model of an impeller with defect-free blades and one blade with a crack were carried out. The model of a linear oscillatory system with one degree of freedom with an impulse response was considered as a model of a blade without a crack, and the model of a blade with a crack was the same model with a piecewise linear characteristic of the restoring force.

To analyze the effectiveness of diagnostics using bispectrums, the influence of various factors was analyzed, namely: the presence of an additive Gaussian noise; possible disagreements in the values of the natural frequencies of the blades and the possible occurrence of subharmonic vibrations. The results of modeling and bispectral analysis of vibroacoustic signals are presented, indicating that the amplitude value of the obtained bispectrums, used as a diagnostic sign, increases with the appearance and development of blade damage. The author points out the possibility and efficiency of using bispectrums for diagnosing a small fatigue crack in the problems of vibroacoustic diagnostics of impeller blades at stationary operating modes. At the same time, the paper does not provide the results of experimental verification of the proposed dynamic model of a gas turbine blade and its adequacy to real blade defects (crack).

In [9], in the study of diagnostic signs of the state of the blades, the methods of multidimensional spectral analysis, time-frequency transformations, wavelet transformations and dimensionless amplitude characteristics of the vibroacoustic signal were used. The paper proposes to use new promising methods of time-frequency analysis, which make it possible to obtain information not only about the presence of certain frequency components in the signal, but also about how these frequency components change over time when the technical state of the blades changes. The disadvantage of this work is the lack of an experimental rewrite of the proposed diagnostic signs.

Developed in the late 90s by S. Saprykin the technology of vibration control and vibration diagnostics of the GPU – 16 with the DZ-59 engine is based on the results of experimental studies. Diagnostic signs were found, establishing a connection between the growth of certain components of the vibration spectra and the phase relationships between harmonics and the presence of specific defects. Regarding the state of the blades, in the high-frequency range up to 10,000 Hz, characteristic regions are monitored, due to the frequencies of rotation of the rolling elements of the bearings and the frequencies of passage of the working and guide blades.

So, for LPC, characteristic frequencies are characterized by working blades f_{131}, f_{243}, f_{343}, f_{443}, f_{543}, f_{643}, f_{743}, and guide blades f_{148}, f_{248}, f_{352}, f_{452}, f_{552}, f_{652}, f_{790}. For HPC – working blades f_{155}, f_{555}, f_{669}, f_{969}; guides f_{148}, f_{548}, f_{660}, f_{960}. For S working blades of the first and second stages: HPT – f_{172}, f_{268}, LPT – f_{170}, f_{256}, HPT guide blades – f_{150}, f_{II48}; LPT f_{156}, f_{II48}; ST – f_{140}, f_{II40}. Vibration levels at the blade passing frequencies were also determined.

In the same period A. Barkov was found that a diagnostic sign of blade defects is an increase in low-frequency vibration at the kf_{ob} harmonics (that is, one of the signs of impeller breakage), supplemented by an increase in harmonics with the same frequencies in the envelope range, and the levels of these harmonics can exceed the levels of blade harmonics.

The main difference between the signs of blade defects and impeller breakage is considered to be the predominant growth of kf_{ob} harmonics in the vibration envelope spectrum of the body, and if the machine has several impellers, then the increase in kf_{ob} harmonics in the body vibration envelope spectrum of the defective wheel, and not all wheels mounted on one shaft.

So, **Fig. 2** shows the spectra of the envelope vibration of a multistage compressor with an impeller strike and a blade defect. As seen from **Fig. 2** in the vibration envelope spectra with blade defects (b) the number of components with | frequencies kf_{ob} and their level is significantly higher than with the impeller break (**Fig. 2, *a***).

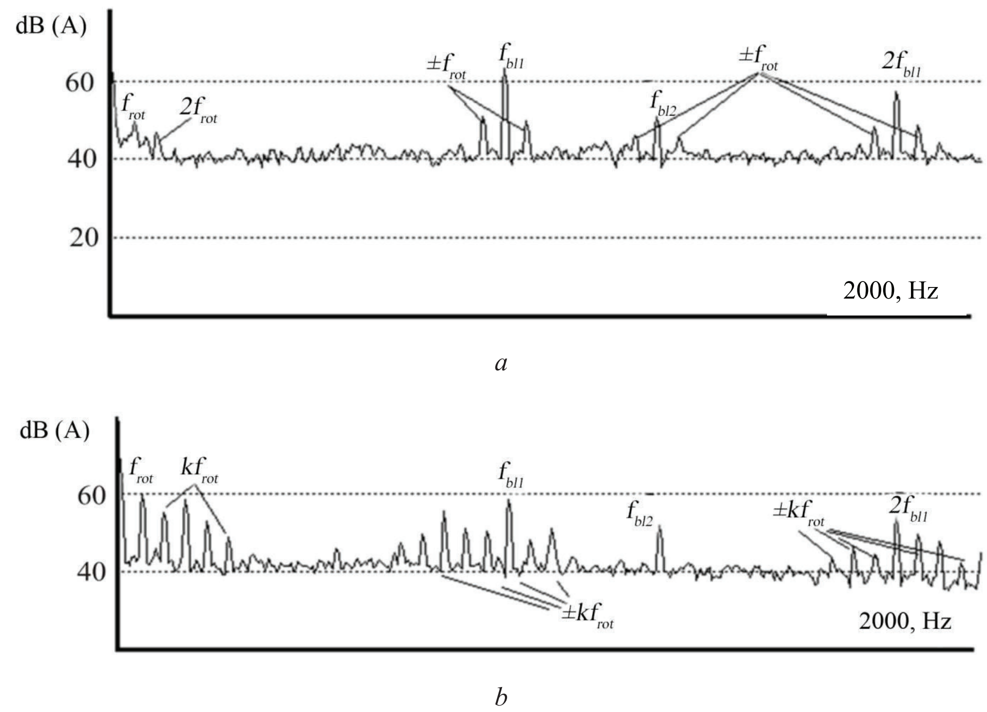

Fig. 2. Spectra of the envelope vibration of a multistage compressor: *a* – with an impeller strike; *b* – a blade defect.

Experimental studies of the vibration state of the GTK-10 GPA using spectral analysis [10] showed that in the high-frequency range the frequencies of excited vibrations are generated by rotor harmonics with multiplicity k and multiples of the number of blades of the j-th level (z_j). Each j-th level of SO and LPT generates vibration, the frequency of which is k_z times greater than the rotor frequency. In the high-frequency range of the spectrum, these frequencies contain a pronounced discrete character and exceed the level of acoustic noise by 20–30 dB. In the GPU GTK-10 frequencies, excited by the blades, multiples of $z_j f_j$ are at the 21, 29, 35, 38, 50, 56, 90th harmonics.

In the spectrum of the high-frequency range, the frequencies of natural vibrations of the working blades and the blades of the guide vanes were found; when they coincide with the harmonics of the rotor, they form resonant operating modes. An experimental study of the high-frequency spectrum has shown that the levels of vibration acceleration of the blade vibration measured on the bearing housings can reach 250–300 m/s^2 and serve as diagnostic signs of a defect in the GPU flow path.

The methods considered above require a significant amount of preliminary experimental research to identify diagnostic signs based on establishing a relationship between the growth of certain components of the vibration spectra and phase relationships between harmonics and the presence of specific defects. At the same time, they have a practical implementation, since they allow diagnosing the technical condition of blades of a particular type of GPU.

2. 3. Diagnostic methods based on the analysis of the processes of aerodynamic interaction of the working and guide blades and direct aerodynamic calculation of the profiles relative to the GPU blades

The methods belong to the third group of methods for diagnosing the technical state of the GPU blades, which are quite new and are at the stage of development.

In [11] it is noted that the processes of aerodynamic interaction of the working and guide vanes can be diagnostic signs of the presence of a crack in the blade, especially at an early stage. So, as a result of aerodynamic interaction, each rotor blade forms a rim to a degree, the shape of which depends on the nature of the oscillation of the rotor blades, in turn is determined by its rigidity (whether there is a crack or not) and by the state of the blade surface (dents, etc.). The procedure for isolating the informative part of the signal is considered, which refers only to the working blades of the stage, is diagnosed from the total vibroacoustic signal accompanying the GPU operation. In this case, the parameters of the distortion of the shape of this signal (spectral, phase, statistical), which appear when defects of the blade occur, can be used as diagnostic signs of the state of the working blades.

It is proposed to use the following diagnostic signs:

– coefficient of nonlinearity of the spectrum of blade harmonics of the investigated degree:

$$D_1=(\Sigma A_l)/A_1, \quad (1)$$

where A_l – the amplitudes of the higher harmonics of the coherently accumulated spectrum of blade harmonics, starting from the 2nd; A_1 – the amplitude of the 1st harmonic.

– kurtosis coefficient of the probability density of the distribution of amplitudes:

$$D_2=\mu 4/\delta-3, \quad (2)$$

where μ – the central moment of the fourth order; δ – the standard deviation;

– deviation of the signal form from the ideal, corresponding to the defect-free state of the blades.

$$D_4=\Sigma|(x_k+|x_{\min}|)-(x_{\max}+|x_{\min}|)x\cos(z\omega_p k\Delta)|, \quad (3)$$

where x_k, $x_{\min}$, $x_{\max}$ – the current, minimum and maximum ordinates of the coherently accumulated signal form, respectively.

The signs listed above can be used both separately and in the form of a diagnostic parameter formed in a certain way.

The paper also presents the results of the practical implementation of the method under consideration with respect to the first stage blades of the NK-12ST aircraft engine as part of the GPA-

Ts-6,3 and concludes that additional studies are necessary in order to use the proposed method for diagnostics of other types of GPU [11].

In [12], for the first time, it was proposed to use the method of direct aerodynamic calculation of airfoils relative to the GPU blades for diagnosing their condition on the basis that a change in the geometry of the blades, which is caused by their defects, will affect their aerodynamic characteristics, and as a consequence, the GPU technological parameters. The process of flow around an isolated blade is proposed to be described by integral equations of the second kind with respect to the tangential component of the flow velocity. After its value, the aerodynamic characteristics of the blade are determined. In [13], to assess the effect of changing the geometric parameters that determine the configuration of the blade, according to its vibration characteristics, the sectional area of the blades and their moment of inertia are calculated using numerical methods. Various methods of reproducing the geometric configuration of the blade profile are considered using experimental data on the coordinates of a certain set of profile points and some research results of the proposed method are given, which indicate the prospects of its practical use.

3. Results

The results of the analysis of methods for diagnosing the technical state of the GPU blades, classified into three groups, show

– diagnostic methods of the first group cannot be used for determination of the technical condition of the GPU blades during its operation due to the significant complexity of the installation of the root and peripheral sensors, their comparison with the geometric position of a particular blade in the wheel at certain times and the corresponding interpretation of the obtained values in the field of mechanical stresses and deformations;

– diagnostic methods of the second group are overwhelmingly based on dynamic models of GTE, modeling and processing of signals generated by a model of an impeller with defect-free blades and one blade with a crack, etc. At the same time, there are no results of checking the adequacy of the developed models to experimental data, does not allow assessing their effectiveness. Other methods of this group are based on the determination of diagnostic signs based on the results of experimental studies of a specific type of GPU. At the same time, it is not indicated, the obtained diagnostic signs can be used to determine the technical condition of the blades of other types of GPU;

– the methods of the third group are quite new, as indicated by their insignificant quantity. At the same time, they are the most promising since they can be used to diagnose the technical condition of blades of any GPU type.

4. Discussion of research results

The methods of the first group have not found wide practical application for diagnostics of the GPU blades, which is explained by the limitations on the number of sensors installed (depending on the number of blades, the technical condition of which must be determined) and the laboriousness of their installation.

The methods of the second group, in particular those based on the results of experimental studies of the vibration state of the blade blades, may have the prospect of their further application. The limitation of studies of this group of methods is due to the complexity of obtaining diagnostic information from vibro-jets, which requires their installation at points that are, if possible, equidistant from the main sources of hull vibration of the GPU. The prospect of using the methods of the second group is associated with the wider use of transformation methods for processing vibration processes accompanying the GPU operation , which will allow obtaining a diagnostic sign of the technical condition of the blades, will not depend on the GPU type.

The widespread use of methods for diagnosing the blades of the third group, in particular, the method of direct aerodynamic calculation of the profiles of the GPU blades is limited by its insufficiently developed mathematical apparatus. Its further development requires the development of a method for mathematical parameterization of the deformed blade profile, which would make it possible to obtain a more accurate method of reproducing the blade coordinates in comparison with the existing ones. Improvement is also required in the method of assessing the influence of blade deformation on the nature of vibration occurring in the GPU with various mathematical descriptions of these processes by taking into account changes in the geometric characteristics of the blade – cross-sectional area and moments of inertia.

5. Conclusions

Classification of methods for diagnosing the blades apparatus of GPU during their operation is proposed.

The analysis of the methods for diagnosing the GPU blades according to the proposed classification was carried out, as a result of which it was established that today there are no generally accepted methods for diagnosing the technical state of the blades. The latter is due to both the complexity of the diagnostic object itself and the complexity of obtaining reliable information from it for its further processing in order to identify rational diagnostic signs of its state.

At the same time, the methods of direct aerodynamic calculation of airfoils relative to the GPU blades are promising, since their use allows not only to calculate the velocity components, but also all existing aerodynamic characteristics of the blade profiles and to propose mathematical models of the deformation and flow around the GPU blades. However, their practical use requires theoretical substantiation with access to numerous calculation algorithms.

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