The operation of a gas turbine engine (GTE) in a dusty atmosphere leads to wear of the elements of the flowing part and, as a result, to a deterioration in its parameters and characteristics.

Helicopter and tank gas turbine engines operating in a dusty atmosphere, as well as gas turbine units of compressor stations operated in areas with high dust concentrations, are subjected to the greatest wear. When operating GTE under such conditions, the compressor is subjected to stronger wear. In this regard, the task addressed in this paper is determining the effect of abrasive wear of the compressor on GTE parameters. To this end, a method for calculating the GTE characteristics is built, making it possible to take into account the effect of abrasive wear of the flow path and blade crowns of the compressor.

Underlying the calculation method is a nonlinear mathematical model that makes it possible to describe the processes occurring in individual nodes and in the engine as a whole under stationary modes. A feature of this method is the two-dimensional description of the compressor in the engine system. The method reported here makes it possible to quickly estimate the effect of deviation of the geometric parameters of the flow path from the rated values on the characteristics of the compressor and engine as a whole.

The geometric parameters of the degraded-out axial compressor were simulated on the basis of wear data. The parameters and characteristics of the degraded-out compressor, as well as the gas turbine engine as a whole, were calculated. It was found that with a given wear of the flow path of the compressor, the specific power of the engine decreased by 7.5 % while specific fuel consumption increased by 6.4 %, and the stability margin decreased by 11.1 % compared to the original ones.

The results could be used to analyze and predict the operational efficiency of engines when they operate under conditions of high dustiness

Keywords: gas turbine engine, axial compressor, abrasive wear, material erosion, aerodynamic losses

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DETERMINING THE INFLUENCE OF COMPRESSOR FLOW PATH ABRASIVE WEAR ON THE GAS TURBINE ENGINE CHARACTERISTICS

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1. Introduction

During operation, the gas turbine engine (GTE) is influenced by various factors that negatively affect its parameters. One of these factors is the ingress of abrasive particles into the flow path of the compressor and its wear.

A significant impact of sand and dust on GTE performance was identified in the operation of aviation equipment during the period of hostilities in Vietnam, Afghanistan, and Iraq. Fig. 1, in accordance with [1–3], shows the operating conditions of aviation equipment with increased dustiness of the atmosphere.

The same problem was encountered during the development and operation of tank gas turbine engines (the T-80 type tank in the USSR and the Abrams type tank in the USA). This experience, as well as the experience of operating stationary gas turbine units, have shown that the engine compressor is most susceptible to negative impact.

Wear of the flow path of the compressor leads to a drop in its performance, and, consequently, a decrease in power, an increase in the specific fuel consumption of GTE, a decrease in gas-dynamic stability and resource reserves. The reason for the deterioration of the compressor performance when working on dusty air include the following factors:

1) reducing the length of the chord and the camber angle;

2) change in the thickness of the inlet and outlet edges and the blade as a whole;

3) increase in the radial clearance between the working blades and the compressor housing;

4) increasing the roughness of the surface of the blade.

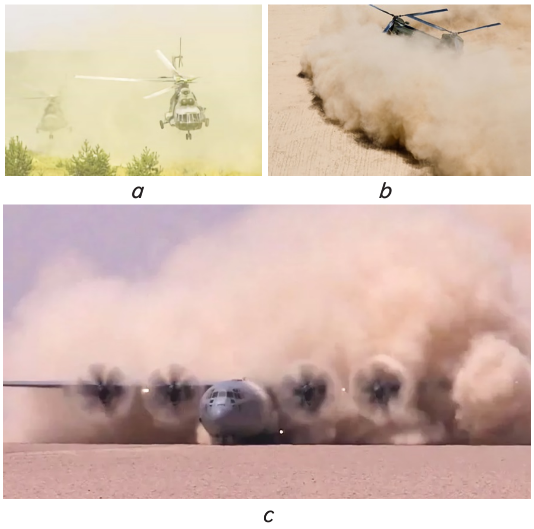


Fig. 1. Operation of air transport in a dusty atmosphere: *a* – flight of the Mi-17 helicopter at low altitudes [1]; *b* – landing of the CH-47 helicopter [2]; *c* – landing of C-130J aircraft in the desert [3]

The degree of damage to the surface of the working and guiding blades of the compressor, as well as other elements of the flow path, depends on the properties of the material (surface hardness, orientation and grain size of the material) and the mode of operation of the engine. The nature of the wear also depends on the properties of the eroding particles (density, size, crumbling ability, hardness, shape, and sharpness of the edges); the concentration of particles in the air; the total mass of particles that have passed through GTE.

Exposure to the flow of centrifugal forces in the interblade channels of rotor blades leads to the movement of heavier abrasive particles in the radial direction. As a result, the peripheral area of the flow path is subjected to more intensive wear. These processes are intensified as they move along the flow path with increasing pressures and decreasing areas of flow sections.

Consequently, the operation of a gas turbine engine in a dusty atmosphere leads to a significant change in its geometric parameters, makes adjustments to the operation of the compressor and engine as a whole. The nature of the change in these parameters under operating conditions for a particular type of engine should be analyzed and evaluated. The results of such studies are necessary to assess and predict changes in the power of GTE (or its thrust), specific fuel consumption, reserve of gas-dynamic stability.

2. Literature review and problem statement

The data given in the literature indicate a change in the thermodynamic and gas-dynamic parameters of engines operating in a dusty atmosphere. For example, paper [4] reports the results of a study of the deterioration of the JT9D engine and its causes. The study was based on historical records and data obtained from five airlines, two airframe manufacturers, and Pratt & Whitney Aircraft. According to these data, it was found that in 40 % of the engines their parameters decreased due to erosion of the flow path. Work [5] shows that the loss of power and reserve of gas-dynamic stability as a result of erosion of the flow path of the compressor caused the removal of some helicopter engines from service after less than 20 hours of flight time.

Particle deposition on aerodynamic airfoils and heat exchange surfaces of the air cooling system, according to [6], can lead to a deterioration in the aerodynamic and thermodynamic properties of these components.

In order to reduce the influence of dustiness of the atmosphere on the operation of the engine, dust protection devices are used [7, 8], the designs of which are constantly being improved [9, 10]. Hardening coatings of the compressor blades with various compounds are also used: TiC-CrC, ZrN-CrN, TiN-ZrN, TiN-CrN, TiN-AlN [11].

Thus, works [4–6] indicate the existence of a problem of the influence of erosion wear on the operation of the engine, while studies [7–11] present ways to prevent wear. However, the use of dust protection devices and various coatings of the blades does not make it possible to completely eliminate wear.

Many papers [12–20] report the analysis of the effect of wear of the flow path in multistage compressors and individual stages. These works can be divided into two categories: experimental methods for studying the deterioration of compressor parameters [12–14] and methods for mathematical modeling of the effect of erosion on these parameters [15–20].

In work [12], experimental studies into the analysis of the effect of dusty air on the operation of the turboshaft GTE compressor were carried out. Simulation of the compressor operation in a dusty atmosphere was performed by supplying abrasive elements in the form of sand to the input to it. The displacement of the compressor characteristics after passing through its flow path of 16 kg of abrasive material is presented. An increase in the radial clearance from 0.2 mm to 1.1 mm was also established. It was shown that wear of the flow path leads to a decrease in the reserve of gas-dynamic stability by 12.5 % and by 11.4 % at rotational speed $\bar{n}=0.89$ and $\bar{n}=1.0$, respectively.

In work [13], as a result of experimental and theoretical studies of compressor blades undergoing erosion, the limit ratio of particle size to the rate of their contact with the material is determined.

Paper [14] reports the results of testing a six-stage compressor. In the first case, wear was simulated by damaging the leading and trailing edges, and in the second, rounding of the rotor blade blades in the periphery was performed. To describe the wear of the blade, the parameter *Kv* is used – the ratio of the wear area of the blades of the rotor blades (RB) and guide vanes (GV) to the surface area of the blades of the original compressor.

As a result, linear dependences of changes in mass flow, compressor efficiency, and stability reserve on this parameter are obtained.

The results of experimental studies [12–14] indicate a significant effect of erosion wear on the characteristics of the compressor but do not demonstrate a deterioration in the parameters of the engine as a whole, and can be used in further theoretical studies.

With the development of the capabilities of computer technology, methods of mathematical modeling of erosion wear are used. Thus, in work [15], a method of numerical modeling of flow parameters in the flow path of a multistage axial compressor is given, taking into account the wear of the blades using the Ansys CFX software module. The effect of dust erosion on the change in the gas-dynamic characteristics of the compressor is estimated by taking into account the amount of chord wear in the peripheral part of the blades and the magnitude of the radial clearance. A linear decrease in the chord according to the height of the blade is adopted, as well as equal values of airfoil wear near the leading and trailing edges. Since the blades of the rotor blades, according to the authors of [15], wear more intensively, the wear of the guiding vanes is neglected in the work. As a result, it was found that after 780–790 hours of operation of the TV3-117 engine in a dusty atmosphere, the gas-dynamic stability of the compressor decreases by 15 % and a surge occurs.

In work [16], based on the method of calculating the parameters of the compressor at the middle radius [17], an assessment of the effect of blade erosion on the total characteristics of the compressor is carried out. Similarly to [15], the reduction of the chord in the height of the blade is assumed to be linear, and the amount of wear of the leading and trailing edges is the same. It is also assumed that the maximum thickness of the airfoil and its position along the chord, the shape of the midline, the stagger angle of the airfoil and the radial clearance do not change when determining the total characteristics. Wear accounting takes place at the middle radius. It should be noted that the accepted models of wear in these works do not fully reflect the real picture of wear. Thus, in work [18] it is indicated that the erosion of the blades has a nonlinear in height nature and the intensity of wear at the leading and trailing edges is different, and the wear itself is manifested both on the rotor blades and on the guiding vanes. Also, the shapes of the airfoils and their maximum thicknesses do not remain constant, and the rotary guides can have very significant wear.

Paper [19] reports an approach to assessing the influence of nonlinear erosive wear of the rotor blade chord in terms of blade height on the characteristics of a helicopter GTE compressor stage using the Ansys CFX software module. It is established that the results of the calculations of characteristics with the same wear of the chord (2 mm) in the peripheral section, but with different distributions in the height of the blade, differ significantlly.

Study [18] also uses the Ansys CFX package to assess the effect of wear on compressor parameters. The geometric parameters necessary to obtain solid-state models of compressor blade crowns are determined by optical-electronic measurements of the geometry of degraded blades.

In work [20], to assess the change in the geometric parameters of the airfoils, the preparation of degraded blades in several sections in height was performed, followed by the creation of micro sections and their processing. To predict changes in the characteristics of a multistage axial compressor as a result of erosion wear, a two-dimensional axisymmetric mathematical model was used, which was supplemented by generalized experimental data on purges of degraded flat gratings.

The above review of the techniques for considering the wear of compressor blades [15, 16, 18–20] reveals that both methods for calculating compressor parameters based on one-dimensional calculation of the average radius and methods for calculating the spatial flow are used in practice. It is worth noting that works [15, 16, 18–20] do not describe the effect of erosion wear on the engine parameters as a whole.

In addition to assessing the effect of erosion wear on the parameters of the compressor, mathematical models are used to take into account the effect of erosion on the characteristics of the engine as a whole. In work [21], the deterioration of the engine performance as a result of operation is simulated by shifting the characteristics of the main components by introducing correction factors for the parameters of these components. The same approach is described in [22], where the commercial GasTurb software package is used to predict the change in the parameters of the gas turbine engine over time [23]. The characteristics of the compressor and turbine in the GasTurb software are set as initial data and are determined from the libraries of characteristics of these nodes. Degradation of performance is simulated by entering corrections to the initial characteristics of undegraded engine components in the form of a degradation parameter.

The disadvantage of works [21, 22] is the lack of calculation of the characteristics of degraded-out units, and wear is modeled by introducing correction coefficients to the initial characteristics.

More accurate are the methods proposed in [24, 25]. Thus, in work [24], a model of the Siemens V94.2 engine is presented, in which the deterioration of the parameters is simulated on the basis of calculating the total characteristics of the compressor and turbine at the average radius, taking into account wear. It is worth noting that wear in the cited work is understood as a «combined fault model» of the compressor and turbine. That is, the deterioration of the parameters of the first stages of the compressor is influenced by pollution, the last stages by erosion, and at all intermediate stages there is a uniform change in the influence of these factors. The deterioration of the total characteristics of the compressor and turbine is simulated by introducing correction coefficients to the efficiency and the degree of increase or decrease in pressure of a particular stage. In work [25], a model of the engine with a step-by-step description of the compressor at the middle radius is proposed. However, the deterioration of the compressor's performance is simulated only by an increase in roughness and radial clearance. Changing other geometric parameters of the compressor in the engine system is not considered.

To analyze the effect of erosion wear of the flow path of the engine on its parameters, methods for calculating thermogas-dynamic parameters in the axial multistage compressor [26–28], in the compressor and turbine [17, 29], as well as in the combustion chamber [30], which are implemented in mathematical models of the gas turbine engine, can be used. However, the above calculation methods are also based on the crown models of blade machines, which describe the processes in a one-dimensional statement («calculation by the average radius»).

The presented mathematical models of GTE [21–29] take into account abrasive wear on the basis of methods for calculating the thermogas-dynamic parameters of the nodes in a one-dimensional statement, or do not calculate the characteristics of degraded-out units at all but simulate wear with correction coefficients to the initial parameters of these nodes. The disadvantage of one-dimensional calculation in relation to the accounting for wear is that the flow path wears out to a greater extent in the peripheral region, and the calculation at the average radius does not make it possible to take that into account.

Thus, to take into account the influence of uneven wear of the blades in height, it is advisable to rely on the crown calculation of the compressor in a two-dimensional setting when building a GTE model, for example, [20, 31, 32].

3. The aim and objectives of the study

The purpose of this study is to devise a method for calculating the thermogas-dynamic parameters and characteristics of the engine, which makes it possible to take into account the wear of the flow path and the blade crowns of the axial compressor. This will make it possible to analyze and predict the operational efficiency of engines when they operate under conditions of high dustiness of the air.

To accomplish the aim, the following tasks have been set:

– to simulate the geometric parameters of a degraded-out axial compressor on the basis of available experimental data on wear;

– to improve the method of calculating the thermogas-dynamic parameters and performance characteristics of the gas turbine engine in order to take into account the effect of erosive wear of the flow path of the compressor on the basis of its two-dimensional model, by upgrading the compressor model;

– to conduct estimation studies into the effect of wear of the flow path on the performance characteristics of the compressor and engine as a whole.

4. The study materials and methods

Our study is based on the use of theoretical methods of modeling and calculation of thermogas-dynamic processes in a gas turbine engine and its elements.

A turboshaft gas turbine engine with a single-shaft gas generator and a free turbine was chosen as the object of research. A spatial image of the flow path of the engine under study in accordance with [33] is shown in Fig. 2.

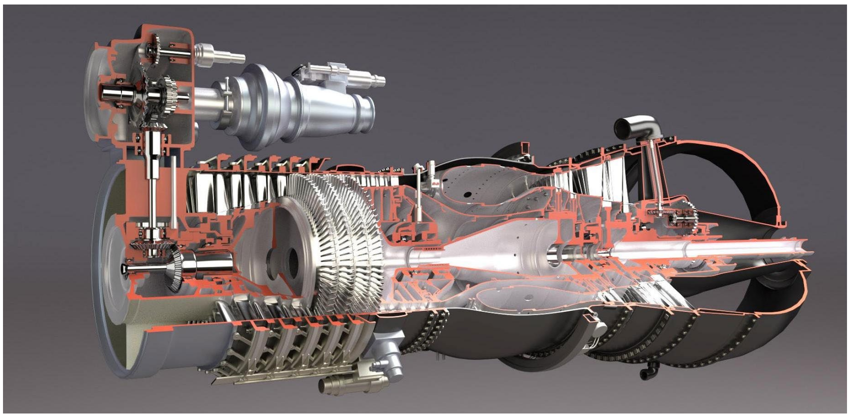


Fig. 2. Spatial representation of the flow-through part of a gas turbine engine in accordance with [33]

The compressor of the object under study is axial, it has 12 stages. Guide vanes I, II, III, and IV (GV1, GV2, GV3, GV4) of the stages and the inlet guide vane (IGV) are made rotary. The program for adjusting the engine with rotary GV is shown in Fig. 3.

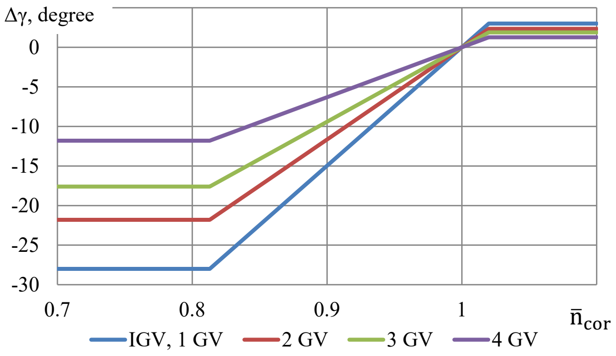


Fig. 3. Program for adjusting rotary guides depending on the corrected speed

Fig. 3 shows the corrected speed in dimensionless form. It is related to its value in the design mode.

To determine the geometric parameters of the degraded-out compressor, work was chosen [20]. Unlike [15], where there are data on wear only in the peripheral section of RB, work [20] reports the parameters of degraded blades of RB and GV on the periphery and middle radius.

To analyze the working processes in the engine, the method of calculating the parameters of the turboshaft gas turbine engine that we developed [34] was used. Underlying the method is a nonlinear mathematical model of GTE, which makes it possible to describe the established processes occurring in individual nodes and in the engine as a whole. The model is built on a modular principle. The module for calculating the parameters of a multistage compressor has a two-dimensional process detail (2D).

The parameters of the compressor necessary to solve the system of equations describing the working process in GTE were obtained using the method of calibration gas-dynamic calculation of the two-dimensional flow in an axisymmetric statement. The method of calculating the compressor makes it possible to reflect the influence of various factors on the characteristics of the engine as a whole. These include changing the geometric parameters of the flow path and the blade crowns in different sections along the radius, adjusting by changing the angles of installation of the rotary GVs, selecting and passing the working fluid from the flow path. The method for calculating the compressor makes it possible to approximately take into account the effects of turbulent transfer of flow parameters in the radial direction, as well as the change in the thickness of the end boundary layers, taking into account the supply of energy from the flow core. Turbulent mixing makes adjustments to the process of flow formation and significantly affects the radial plots of flow parameters. The use of a conditional separation of the energy exchange process in the blader crowns and turbulent exchange makes it possible to simplify the description of the real working process in the stage.

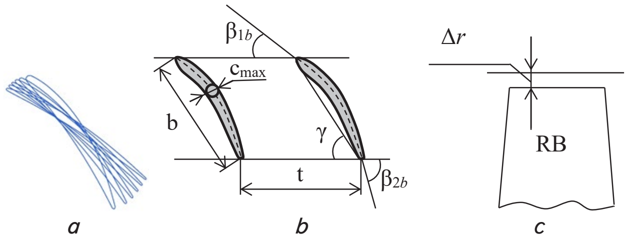
Turbulent exchange is described using the equations of mass, momentum, and energy transport by large-scale turbulent vortices. This makes it possible to assess the degree of equalization of the radial unevenness of the flow in the stage and the multistage compressor.

5. Results of calculating the thermogas-dynamic parameters of the turboshaft gas turbine engine, taking wear into account

5. 1. Simulation of geometric parameters of blade crowns of a degraded-out compressor

To assess the effect of wear of the flow path of the compressor on the parameters of the gas turbine engine, it is necessary to modify the previously developed method for calculating the thermogas-dynamic parameters of the gas turbine engine [34]. It is necessary to include a two-dimensional crown model of a multi-stage compressor, which makes it possible to take into account the change in geometric parameters for the height of the blade with the ability to simulate the wear of the flow path, as well as the deterioration in the quality of streamlined surfaces.

To calculate the characteristics of the compressor in a two-dimensional setting, it is necessary to specify geometric parameters for the height of the blade crowns and the flow path of the degraded-out compressor. Such parameters include the blade angles of inlet and outlet of the airfoils of the blades of rotor blades (β) and guide vanes (α), stagger angles γ, chords of airfoils b and maximum thicknesses of airfoils c_{max}. In addition to the above parameters, you need to specify the shape of the midline of the airfoils, the number of blades Z, the radial clearance Δr, roughness, etc. These parameters are shown in Fig. 4.



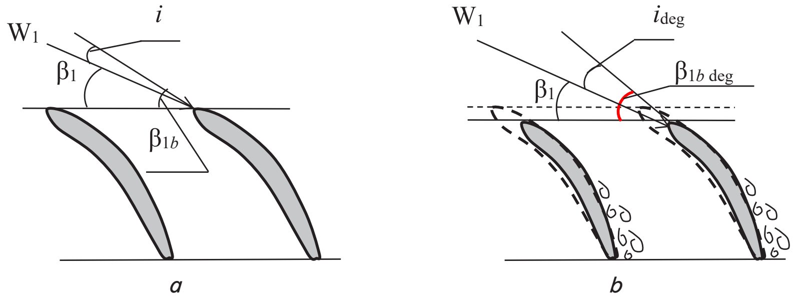
a *b* *c*

Fig. 4. Assigned geometric parameters of the blade crown: *a* — cross-sections of the blade airfoil at different radii; *b* — parameters of the airfoil cascade; *c* — the value of the radial clearance

According to the data given in the literature, the wear of the blade crown is primarily manifested at the leading and trailing edges. A decrease in the chord in these areas (Δb_1 and Δb_2) entails an increase in the blade angle of inlet (β_{1b}) and a decrease in the blade angle of outlet (β_{2b}). This leads to a significant decrease in the camber angle of the airfoil ($\theta=\beta_{2b}-\beta_{1b}$). If the middle line of the airfoil is shown by an arc of a circle, then the wear of the leading and trailing edges have an equivalent effect on the camber angle. That is, with the same amount of wear of the leading and trailing edges, the blade angles of entry and output are changed by equal absolute values. However, if the middle line of the airfoil is described by a parabola or other curve, then its curvature along the airfoil is unevenly distributed, respectively, the wear of the leading and trailing edges affects the camber angle differently.

When the blade wears, the incidence angle on the airfoil changes significantly $i=\beta_{1b}-\beta_1$ (Fig. 5, *a*), which determines the nature of its flow. Wear of the airfoil along the leading edge leads to an increase in the incidence angle. This, in turn, at significant values in the modes rated for the initial airfoil, can lead to a disruption of the flow from the rarefaction of the airfoil (Fig. 5, *b*).

When the trailing edge of the rotor blade wears, the blade angle of the airfoil output and the incidence angle to the next guide vane change. This can lead to a disruption of the flow from the pressure of this airfoil. The velocity triangles and lattices of the airfoils for this case are shown in a simplified form in Fig. 6.

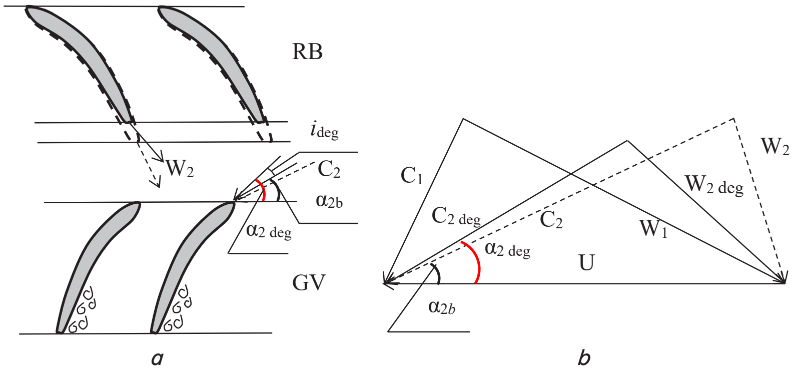


a *b*

Fig. 5. Flow around the airfoil at different incidence angles: *a* — initial incidence angle; *b* — increased incidence angle; ——— — degraded airfoil; - - - - - - - - — original airfoil

Wear of the airfoils leads to a change in the characteristics of the cascades. This entails a decrease in the angle of rotation of the flow, an increase in the loss coefficient ξ, and a decrease in the range of discontinuous modes of operation of the cascades and the blade crown as a whole. Fig. 7 shows the dependences of the incidence angle $\Delta\beta$ and the loss coefficient ξ on the incidence angle for the original and degraded airfoil in the cascade.

To assess the degree of wear of the elements of the flow path of the compressor during operation, the change in the radial clearance and chord of a limited number of blade crowns is controlled. Often this is the first rotor blade and several blade crowns, which are accessed through the viewing windows. For a more detailed analysis of erosion wear, the compressor may be left without blades during overhaul, or the blade crowns can be prepared after the engine is decommissioned. As a result of preparation, the coordinates of the back and trough of the degraded airfoil are obtained in several sections according to the height of the blade.



a *b*

Fig. 6. Flow in the lattice of the airfoils during wear of the trailing edge: *a* — cascades of the rotor blade and guide vane airfoils; *b* — velocity triangles; ——— — degraded airfoil; - - - - - - - - — original airfoil

Based on the obtained coordinates of the airfoil, you can find the coordinates of its midline. They are determined by entering the circle airfoil into the contours using a special subroutine. A comparison of the original and degraded airfoils, as well as their middle lines, is shown in Fig. 8. Based on the data on the wear of the chord of the airfoil, as well as data on the shape of the midline, it is possible to determine the change in the blade angles of the airfoils of the blade crowns.

In general, when the middle line is represented by an arbitrary curve (Fig. 9), in order to determine the blade angles of the airfoil, it is necessary to know the coordinates of the midline points and fit them to dependence $y=f(x)$.

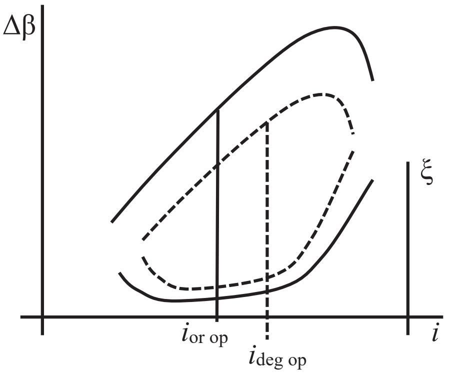


Fig. 7. Dependence of the angle of rotation of the flow and the coefficient of losses in the cascade on the incidence angle; ——— — original airfoil; - - - - - - - - — degraded airfoil

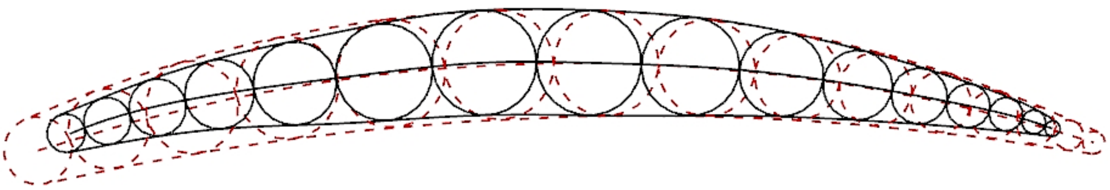


Fig. 8. Comparison of the original and degraded airfoils: ——— – degraded airfoil; - - - - - - - - – original airfoil

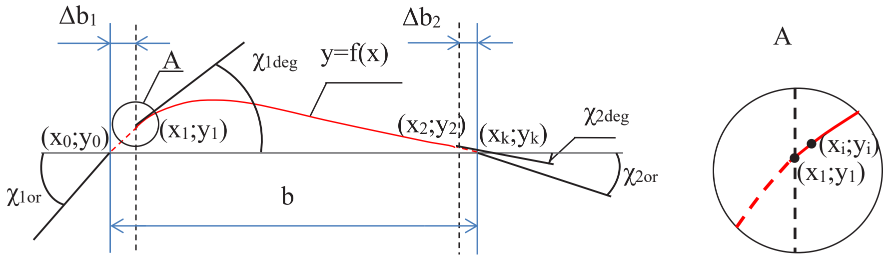


Fig. 9. The middle line of the airfoil represented by an arbitrary function $y=f(x)$ or a set of points

In Fig. 9, point 0 and point K are the leading and trailing edges of the original airfoil, points 1 and 2 are the leading and trailing edges of the degraded airfoil.

In the case when the middle line of the original airfoil is given by the function $y=f(x)$, according to the available values of chord wear at the leading ($\Delta b1$) and trailing ($\Delta b2$) edges, we determine the angles of inclination of the tangents to the airfoil midline at the leading (χ_{1deg}) and trailing (χ_{2deg}) edges:

$$\chi_{1deg} = \mathrm{arctg}\left(\frac{dy}{dx}\right)_i, \qquad (1)$$

$$\chi_{2deg} = \mathrm{arctg}\left(\frac{dy}{dx}\right)_j, \qquad (2)$$

where $(dy/dx)_i$ is the derivative of the function $y=f(x)$ at the point $x=x_i$, $(dy/dx)_j$ is the derivative of the function $y=f(x)$ at the point $x=x_j$.

In the case where the middle line of the airfoil is specified by coordinates, the angles of inclination of the midline of the degraded airfoil are determined using the finite difference approach, using one-way differences:

$$\chi_{1deg} = \mathrm{arctg}\left(\frac{y_i - y_1}{x_i - x_1}\right), \qquad (3)$$

$$\chi_{2deg} = \mathrm{arctg}\left(\frac{y_j - y_2}{x_j - x_2}\right), \qquad (4)$$

where $(x_1; y_1)$, $(x_2; y_2)$ are the coordinates of the end points of the midline of the degraded airfoil located at a distance of Δb_1 and Δb_2 from the leading and trailing edges of the reference airfoil, $(x_i; y_i)$, $(x_j; y_j)$ – coordinates of points located at a given distance from the end points of the degraded airfoil.

After that, the blade angles of entry and exit of the degraded airfoil are determined:

$$\beta_{1bdeg} = \gamma - \chi_{1deg}, \qquad (5)$$

$$\beta_{2b.deg} = \gamma + \chi_{2deg}, \qquad (6)$$

where γ is the stagger angle.

Since the angle $\chi_{1deg} < \chi_{1or}$ and the angle $\chi_{2deg} < \chi_{2or}$, with an increase in the wear of the airfoil, the camber angle of the airfoil ($\theta = \chi_2 - \chi_1$) decreases by the amount of $\Delta\theta$:

$$\Delta\theta = \Delta\chi_1 + \Delta\chi_2, \qquad (7)$$

where $\Delta\chi_1 = \chi_{1or} - \chi_{1deg}$, $\Delta\chi_2 = \chi_{2or} - \chi_{2deg}$.

Thus, on the basis of available data on the geometric parameters of the blades and the flow path of the initial compressor, by using the above approach, the geometric parameters of the degraded-out crowns and the flow path of the compressor can be determined. Schematically, a degraded blade crown in comparison with the original one is shown in Fig. 10.

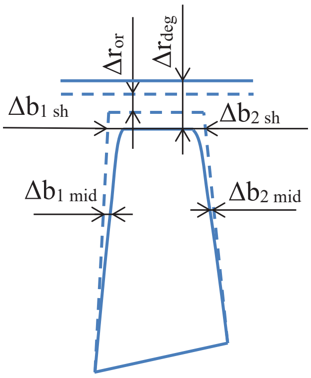


Fig. 10. Schematic representation of a degraded blade crown in comparison with the original one: ——— – degraded airfoil; - - - - - - - – original airfoil

Using the described approach to modeling geometric parameters and the data reported in work [20] on the wear of blades at the periphery and average radius, the geometric parameters of the rotor blades and guide vanes of the degraded-out compressor were determined. The amount of chord wear in the intermediate sections is determined by interpolation, and it is assumed that the bushing section does not wear out.

The amount of wear of the chords of RBs and GVs stage-by-stage for the peripheral cross-section and at the middle radius is shown in Fig. 11.

The amount of bending of the airfoil of the original and degraded blades of RB and GVs depending on the stage number on the periphery and the middle radius are shown in Fig. 12, 13.

Fig. 14, 15 show the change in blade angles along the height of the original and degraded blade edge.

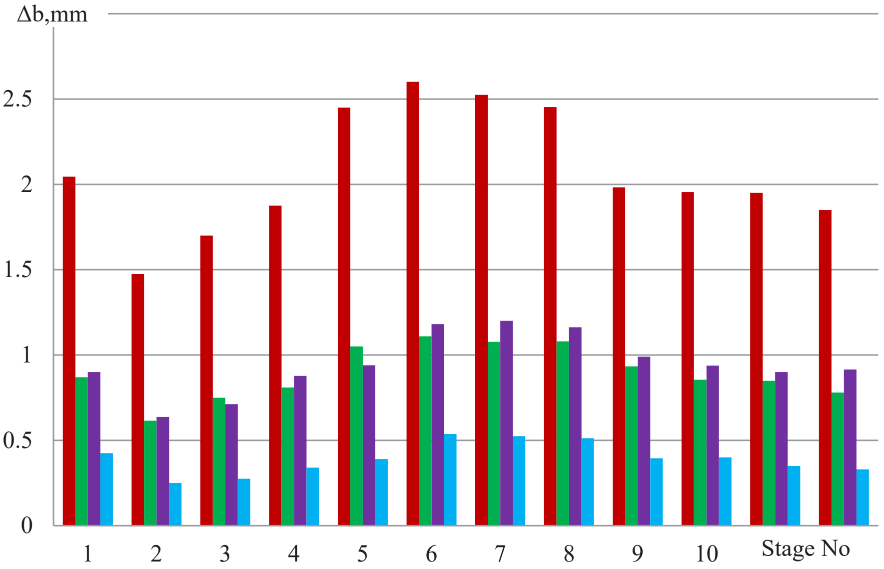
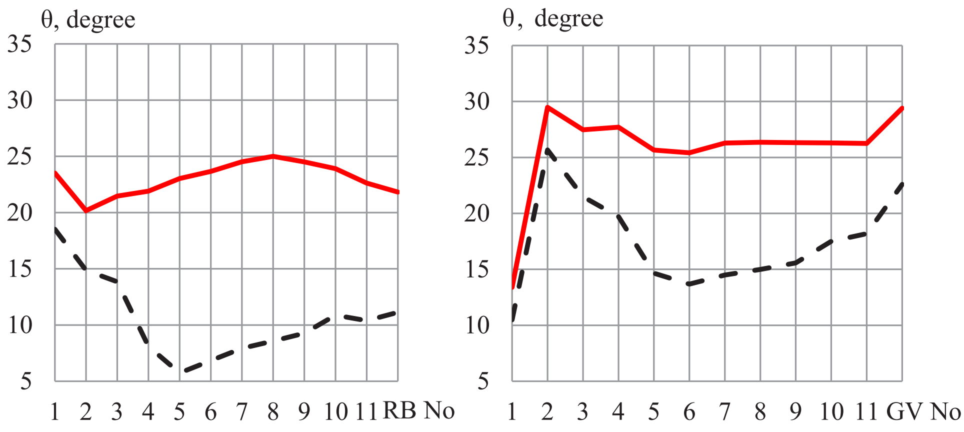
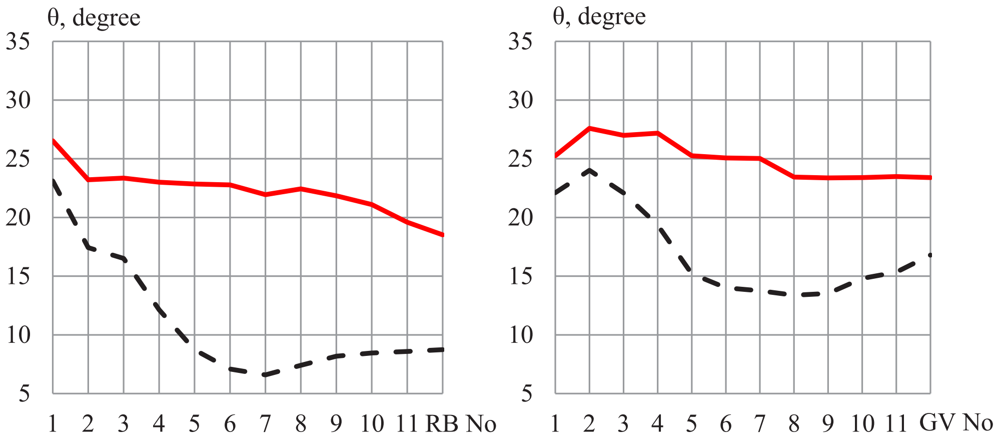


Fig. 11. The amount of wear of blade crowns: 🟥 – wear of the chord of rotor blades in the peripheral cross-section; 🟩 – wear of the chord of rotor blades at the middle radius; 🟪 – wear of the chord of guide vanes in the peripheral cross-section; 🟦 – wear of the chord of guide vanes at the middle radius



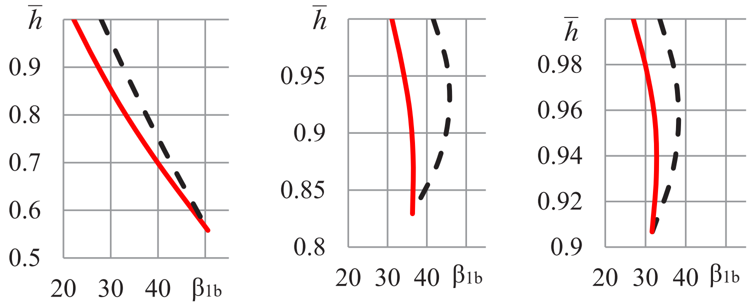
a *b*

Fig. 12. The camber angle of the blade airfoil in the peripheral cross-section: *a* – rotor blade; *b* – guide vanes; ━━ – original compressor; ╍╍╍ – compressor after operation in dusty conditions



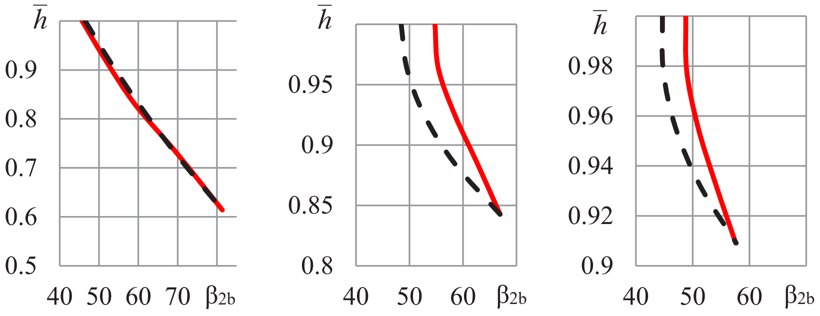
a *b*

Fig. 13. The camber angle of the blade airfoil in cross-section at the middle radius: *a* – rotor blade; *b* – guide vanes; ━━ – original compressor; ╍╍╍ – compressor after operation in dusty conditions



a *b* *c*

Fig. 14. Change of blade angles at the input β_{1b} for the height of the blade of rotor blades: *a* – stage 1; *b* – stage 6; *c* – stage 12; ━━━ – original compressor; ▬ ▬ ▬ ▬ – compressor after operation in dusty conditions



a *b* *c*

Fig. 15. Change in blade angles at the output β_{2b} for the height of the blade of rotor blades: *a* – stage 1; *b* – stage 6; *c* – stage 12; ━━━ – original compressor; ▬ ▬ ▬ ▬ – compressor after operation in dusty conditions

The value of the radial clearance for the original and degraded compressor in accordance with [20] is shown in Fig. 16.

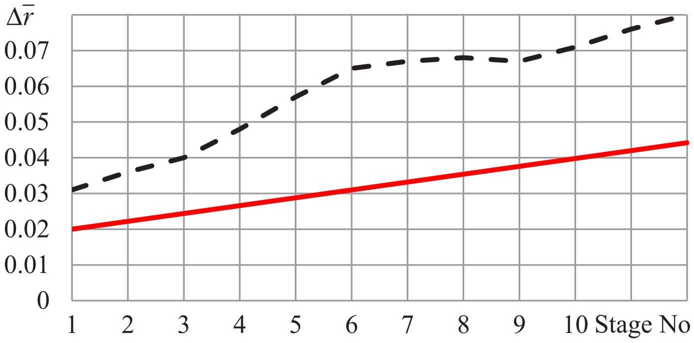


Fig. 16. Change in the radial clearance along the flow path: ━━━ – original compressor; ▬ ▬ ▬ ▬ – compressor after operation in dusty conditions

In addition to changing the above geometric parameters with erosion wear, the roughness of the airfoil increases significantly. Roughness determines the quality of the surface, which also affects the flow of the airfoil. It depends on the height of the protrusions and their distribution over the surface. When the protrusions are below the laminar sublayer, the surface is considered hydraulically smooth, otherwise the surface is considered rough, and is a source of additional hydraulic losses. The equivalent roughness of sand grains k_s is used in accordance with work [35]. Equivalent roughness is understood as a conditional, uniform surface roughness formed by protrusions of the same height, at which the head losses are the same as for real roughness. Given the lack of data on the measurement of this parameter for the object under study during operation, the roughness of the degraded airfoil is taken in accordance with [36]. The amount of roughness for blades with different wear is given in Table 1.

Table 1

Surface roughness of the blade

k_s, µm	Blade wear rate
5	original, undegraded blade
20	degraded blade
40	extremely degraded blade

The presented method for modeling the geometric parameters of a degraded-out compressor allows us to estimate the change in chord, blade angles of the leading and trailing edges, maximum airfoil thickness, radial clearance, as well as roughness.

5. 2. Improvement of the method for calculating the thermogas-dynamic parameters of the compressor to take into account the wear of its flow path

In the mathematical model of the compressor, the method of calculating its thermogas-dynamic parameters with crown-to-crown two-dimensional detailing is used.

To take into account the change in the geometric parameters of the flow path and blade crowns as a result of erosion, dependences were introduced into the method reported in [34] to take into account the influence of the roughness of the surface of the blade crowns, as well as the radial clearance.

Taking into account the influence of the roughness of the blade surface is carried out using the coefficient of friction λ, proposed in work [37]:

$$\lambda=\left\{-1.8\lg\left[\frac{6.9}{\mathrm{Re}}+\left(\frac{k_s/b}{3.7}\right)^{1.11}\right]\right\}^{-2}, \qquad (8)$$

where Re is the Reynolds number defined by the chord, k_s is the equivalent roughness, b – chord airfoil. This coefficient of friction is used to determine the ratio of losses of the original and degraded airfoil in accordance with [38]:

$$\frac{1-\eta_{\mathrm{or}}}{1-\eta_{\mathrm{deg}}}=\frac{(1-k)+k\dfrac{\lambda_{\mathrm{or}}}{\lambda_{\mathrm{or,\,cr}}}}{(1-k)+k\dfrac{\lambda_{\mathrm{deg}}}{\lambda_{\mathrm{or,\,cr}}}}, \qquad (9)$$

where k is the proportion of airfoil losses from total losses. $k=0.4$ for axial compressor and $k=0.7$ for centrifugal compressor according to [39], λ_{or} is the coefficient of friction for the original airfoil, λ_{deg} is the coefficient of friction for the eroded airfoil, $\lambda_{\mathrm{or,\,cr}}$ is the coefficient of friction for the original airfoil at the critical value of the Reynolds number.

The shown ratio is taken into account when determining the total losses of the degraded airfoil. Also, a clarifying dependence is introduced into the method to assess the effect of the radial clearance on the efficiency of the stage in accordance with [40]:

$$\Delta\eta=\frac{0.7(\Delta r/h)\psi}{\cos\beta_m}\times\left[1+10\sqrt{\frac{\varphi}{\psi}\,\frac{\Delta r/b}{\cos\beta_m}}\right], \qquad (10)$$

where Δr is the radial clearance; h is the height of the blade; b – chord in the peripheral section; $\varphi=C_a/U$ – flow rate coefficient in the peripheral section; U is the circumferential component of velocity; C_a is the axial component of the velocity; $\psi=2C_p\Delta T^*/\rho U^2$ – load factor; C_p – specific heat capacity at constant pressure; ΔT^* is the temperature difference in the inhibited parameters in the peripheral section; ρ is density; $\beta_m = =\mathrm{arctg}\left(\left(\mathrm{tg}\beta_1+\mathrm{tg}\beta_2\right)/2\right)$ – the average incidence angle on the airfoil.

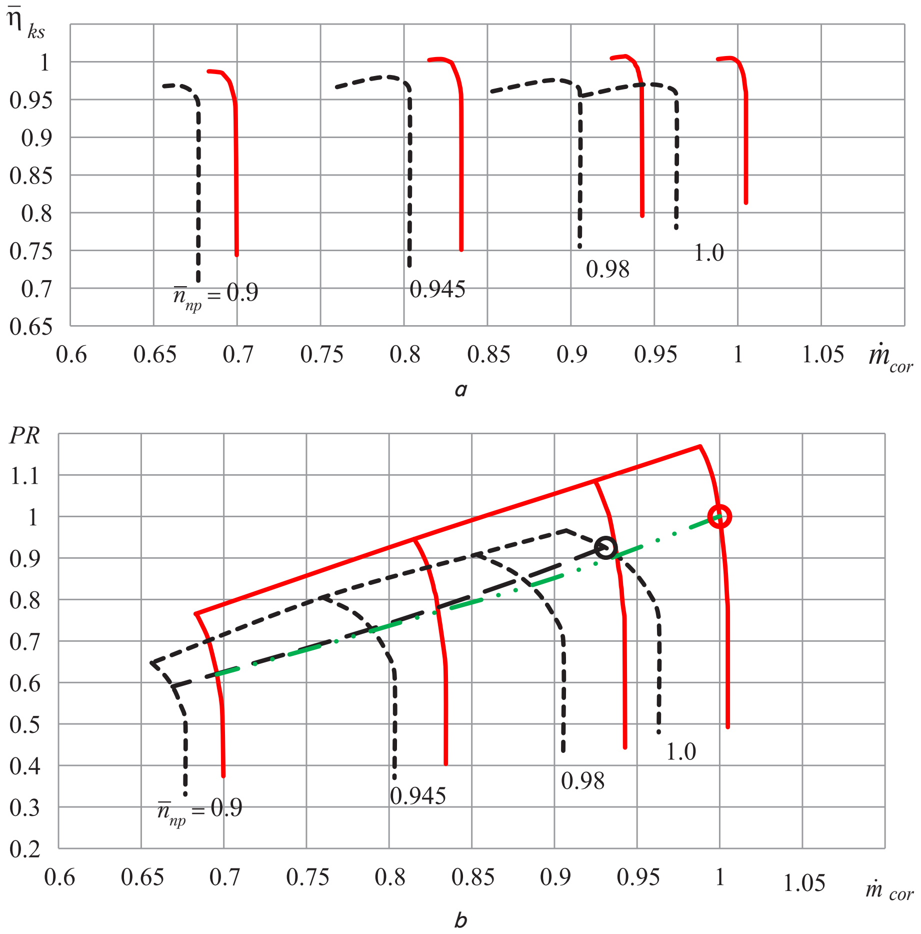
Changes in geometric parameters shall be taken into account in accordance with chapter 5. 1.

5. 3. Analysis of the effect of abrasive wear of the flow path of the compressor on the thermogasdynamic parameters of the engine

The study of the characteristics of the original and degraded-out GTE was carried out under steady operating modes. In the range of corrected speeds considered, the bypass valves were closed. The compressor was adjusted by turning the stator blades (IGV, GV1, GV2, GV3, GV4) according to a given program depending on the rotational speed. Engine control is performed using the program n_{cor}=var, F_{od}=const, i.e., the adjusting parameter is the corrected speed of the gas generator n_{cor}, with the same area of the trailing device F_{od}.

The results of calculating the throttle characteristics of a turboshaft gas turbine engine with the original and degraded flow paths are shown in Fig. 17 in the form of a line of joint modes of operation of the gas generator units. The parameters on the characteristic are related to the corresponding values in the design mode.

It follows from the above plot that the «calculated» mode of the original compressor (as well as the entire characteristic as a whole) is shifted towards lower costs to the point of the «calculated» mode of the degraded-out compressor. At the same time, the pressure ratio increases, and efficiency decreases. In addition to shifting the characteristics of the compressor towards lower costs, the boundary of the gas-dynamic stability area is significantly shifted to the line of operating modes. This fact is due to the deterioration of the flow around the blade crowns, in particular, an increase in the incidence angles. A comparison of the incidence angles under the design mode for the original and for the degraded-out compressors is shown in Fig. 18. Naturally, when approaching the stability boundary, these angles increase.



a

b

Fig. 17. Compressor characteristics: *a* – efficiency factor $\bar\eta_{ks}$; *b* – pressure ratio increase *PR*; ——— – original compressor; – – – – – compressor after working in dusty conditions; – · – – the line of operating modes of the original engine; — — – – the line of operating modes of a gas turbine engine with a degraded-out flow path; ○ – design mode of the original compressor; ○ – design mode of the degraded-out compressor

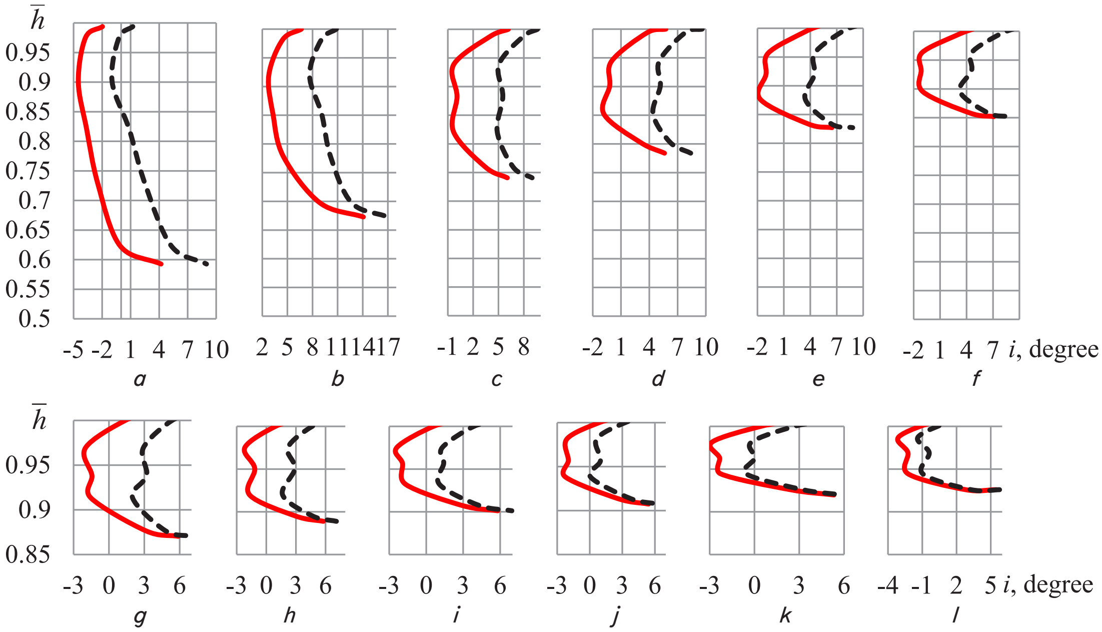


Fig. 18. Distribution of incidence angles according to the height of the blade:
a — rotor blade 1; *b* — rotor blade 2; *c* — rotor blade 3; *d* — rotor blade 4; *e* — rotor blade 5; *f* — rotor blade 6;
g — rotor blade 7; *h* — rotor blade 8; *i* — rotor blade 9; *j* — rotor blade 10; *k* — rotor blade 11; *l* — rotor blade 12;
━━━ — original compressor; ▬ ▬ ▬ ▬ — compressor after operation in dusty conditions

Fig. 19 shows a comparison of the gas-dynamic stability reserves ΔK_y of the original and the abrasive-wear GTE determined in accordance with [41]:

$$\Delta K_C = \left(1 - K_C\right)100\,\%, \qquad (11)$$

where $K_C = \dfrac{PR_s / \dot{m}_{cors}}{PR_d / \dot{m}_{cord}}$ is the coefficient of stability, PR_s – the pressure ratio increase in the compressor at the boundary of gas-dynamic stability, $\dot{m}_{cors}$ – corrected mass flow rate on surge line, PR_d – the pressure ratio increase under the operating mode, $\dot{m}_{cord}$ – corrected mass flow rate at design point.

Fig. 20 shows how the specific power and specific fuel consumption of the engine with the initial and degraded flow path of the compressor change depending on the speed of rotation.

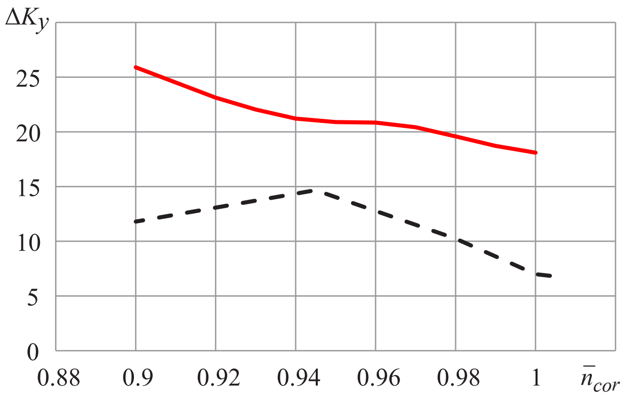


Fig. 19. Change in the reserves of gas-dynamic stability of the original and degraded-out engine depending on the corrected speed of rotation: ━━━ — original compressor; ▬ ▬ ▬ ▬ — compressor after operation in dusty conditions

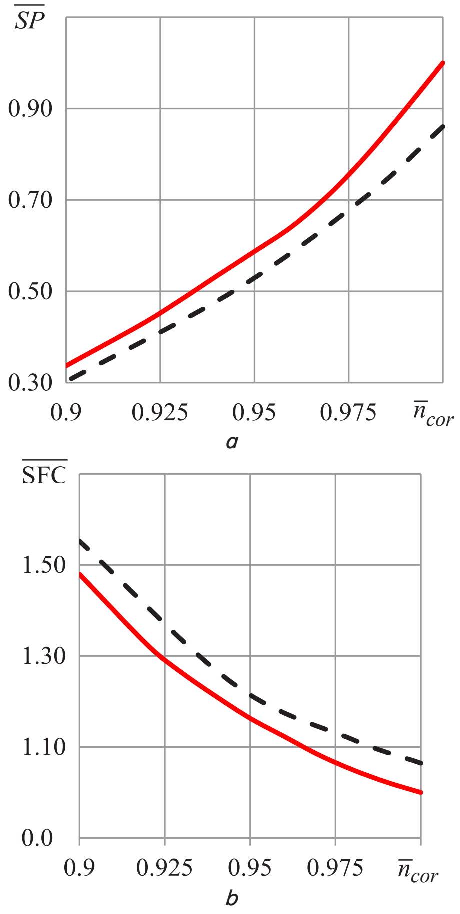


Fig. 20. The throttle characteristic of the original and degraded engine: *a* — dependence of the specific power on the corrected speed; *b* — dependence of specific fuel consumption on the corrected speed; ━━━ — original compressor; ▬ ▬ ▬ ▬ — compressor after operation in dusty conditions

As a result, the specific power of the original engine in the design mode decreased by 14 %, and the specific fuel consumption increased by 6.5 % compared to the design mode of the degraded-out gas turbine engine. Also, the reserve of gas-dynamic stability decreased by 11.1 %.

6. Discussion of results of investigating the effect of abrasive wear on the parameters of the engine under study

An approach to modeling the geometric parameters of the blade crowns and the flow path of the compressor, which have undergone abrasive wear, is proposed. Unlike work [16], where wear was set only at the middle radius, the proposed approach takes into account the nonlinear change in the height of the chord blade, the blade angles of the leading and trailing edges. Also, this approach makes it possible to take into account the change in the thickness and other geometric parameters of the airfoil and flow path necessary to calculate the thermogas-dynamic parameters of a degraded-out compressor (Fig. 11–16).

The method for calculating the thermogas-dynamic parameters of the compressor in the engine system has been improved to simulate the consequences of operating a turboshaft gas turbine engine in a dusty atmosphere. In the initial method for calculating the parameters of GTE [34], dependences were introduced into the model of two-dimensional flow in the compressor to assess the effect of roughness and radial clearance (8) to (10). The advantage of the reported method in comparison with [21–25] is the crown-to-crown two-dimensional detailing of processes in the compressor model, which thereby increases the level of GTE modeling during the analysis of wear. Also, the timing of the calculation analysis is much shorter in comparison with the experimental studies [12–14].

Using the above method, an analysis of the effect of abrasive wear on the thermogas-dynamic parameters of the engine was performed. Fig. 17 shows that due to abrasive wear of the flow path of the compressor, the air flow through the compressor and the engine as a whole and, accordingly, its power is significantly reduced. The reserve of gas-dynamic stability of the engine is reduced (Fig. 19). This fact is explained by the displacement of the operating mode line and the stability boundary (Fig. 17), which is determined primarily by the change in the flow conditions of the blade airfoils and the increase in the incidence angles (Fig. 18).

Fig. 20 makes it possible to evaluate the numerical values of the decrease in specific power and the increase in the specific fuel consumption of GTE under various modes. This is due to a significant decrease in the pressure of the compressor (Fig. 17) as a result of erosion of the flow path and blade crowns.

A limitation of the method for determining the effect of abrasive wear of the flow path of the compressor on the characteristics of the gas turbine engine is the need to specify a large number of geometric parameters of the degraded-out compressor. However, during operation, it is possible to measure only the chords of a limited number of blade crowns. Often this is the first rotor blade and several blade crowns, which are accessed through the inspection windows. Determining the wear of the remaining blade crowns requires that the compressor is devoid of blades.

The disadvantage of the proposed method for assessing engine parameters when operating in a dusty atmosphere is the analysis of the effect of abrasive wear only in the compressor. A possible development of research in this direction may be to supplement this method by taking into account the effect of erosion on other components of the engine.

7. Conclusions

1. The geometric parameters of the flow path and blade crowns of the compressor, which has undergone abrasive wear, are simulated on the basis of available wear data. The proposed approach makes it possible to take into account the change in the chord, blade angles of the leading and trailing edges, the maximum thickness of the airfoil, the radial clearance, as well as roughness.
2. The method for calculating the parameters and characteristics of the gas turbine engine has been improved, including a two-dimensional approach to the blade-to-blade modeling of the flow in the compressor. Dependences were added to the original method to take into account the roughness of the surfaces of the blades and the radial clearance. These additions make it possible to assess the effect of degraded of the blade and the flow path of the compressor on its parameters, as well as the parameters and characteristics of the engine as a whole.
3. The analysis of thermogas-dynamic parameters and throttle characteristics of the helicopter gas turbine engine, which underwent abrasive wear during operation, and their comparison with the corresponding data of the initial GTE was carried out. The results of the calculations showed that with wear of the flow path of the compressor, the specific power of the original engine in the design mode decreased by 14 %, and the specific fuel consumption increased by 6.5 %, compared to the design mode of a degraded-out gas turbine engine. Also, the reserve of gas-dynamic stability decreased by 11.1 %.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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