EFFECT OF COMPRESSOR BLADES’ OPERATIONAL DAMAGES WITHIN AN AIRCRAFT GAS-TURBINE ENGINE ON ITS PERFORMANCE

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ABSTRACT

Damages of compressor blades caused by foreign objects (FO) or bird strike result in a change in the configuration of blades profiles and a decrease in their structural strength. Depending on the damage extent of the compressor blades, as well as on secondary damages and destructions of the structural components of gas-turbine engines (GTE), accidents or emergencies may occur. A decrease in the structural strength of damaged blades is taken into account via chippings’ rating. The effect of compressor blades’ damages on its operational efficiency is not specified. A change in the configuration of the damaged blades’ profiles leads to a change in the flow character, which, in turn, may lead to deterioration of effectiveness of the compressor operation and its characteristics as a blade unit. This research is aimed to estimate some types of operational damages of the compressor blades and their possible effect on the effectiveness of the compressor operation as a blade unit. A change in the effectiveness of the compressor operation as a blade unit was estimated based on the analytical method and via compressor operation simulation using gas...
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dynamics numerical methods, which are based on the computational fluid dynamics (CFD) analysis. The analytical estimation of a change in the airflow through the blade passage for the blade with a damaged leading edge in the form of chipping and the results of CFD analysis have shown a possibility of a change in the effectiveness of the compressor operation as a blade unit and deterioration of the compressor characteristics. A substantial change in the compressor characteristics in case of the damaged blades occurs only within a certain range of rotor speeds and for large damages.

**Key words:** compressor of an aircraft GTE, blade unit, compressor blades, chippings, plastic deformation.


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1. INTRODUCTION

During the operation of civil aircraft (CA) engines, their structural components are exposed to different damaging factors, particularly those, which are connected with temperature and humidity of atmosphere air, environmental pollution, foreign objects (FO) on the air strip (AS) surface and birds in the air. The effect of these damaging factors on the GTE compressor blades leads to their damage. Especially dangerous for CA are damages of compressor blades caused by the effect of FO [1-6] and birds [7-10]. The FO probability and bird strike depends on the GTE type, its location within CA, flying intensity, and quality of airport pavements. FO with the dimensions of less than 70 mcm are classified as dust and the damage of the blade body caused by these FO is characterized as the erosion damage (erosion wear).

The analysis of the data on aircraft GTE operation shows that despite implementation of effective measures at the GTE designing, production and operation stages aimed to prevent operational damages of compressor structural components caused by FO and bird strike, the quantity of engines, taken out of operation ahead of schedule for this reason, still remains rather substantial. Because of GTE compressor blade damage caused by FO strike, up to 30-40%, at an average, of total number of engines are removed from operation ahead of schedule.

Nowadays, the existing methods of GTE protection from damages caused by FO strike do not make it possible to completely prevent GTE damage by FO and to eliminate removing these engines from operation ahead of schedule.

Due to the fact that in future the quantity of civil aviation flights will increase, contemporary designs of GTE and CA will hardly offer in the foreseeable future a positive solution of the problem pertinent to compressor blades’ damage caused by FO and bird strike.

Reducing the adverse effect of FO and bird strike on GTE structures is possible via GTE creation being FO and bird strike-proof, as well as via an increase in the operation efficiency based on the use of calculations’ results, obtained at the designing stage and pertinent to the effect of different types of operational damages on the effectiveness of the compressor operation as a blade unit.
Currently, the principal document regulating the extent of compressor blades’ damage is OST 1 00304-79. This branch standard (OST) allows operation of damaged blades after confirmation of the dynamic strength margin for the whole service life. Operation of GTE with damages is allowed only for definite damage extents, determined by the depth of chipping, its location on the blade body relative to the node of oscillations and so on. Safe operation in this case depends on the results of visual and instrumental monitoring of the blades state without performing of quantitative estimates of service life changing. Such an approach does not always provide the required level of safe GTE use with the damaged compressor blades and effectiveness of the engine operation.

If the damaged blade is repaired through cutting-down of the damaged zone, then it involves certain material costs and, besides, cutting-down operation in some cases cannot be performed in operating conditions.

The repair of the damaged blades through cutting-down of the chippings and removing of the deformed areas allows only partly overcoming a decrease in the fatigue strength of the blades. This operation does not solve the problem connected with the effect of a change in the profile configurations of the damaged blades on the gas-dynamic behavior of the compressor and on the safety of the GTE use with the repaired compressor blades. Large damages may lead to accidents or emergencies caused by both breaking down of the damaged compressor components in flight and its malfunctions caused by a change in the flow character around the damaged compressor components. A change in the airflow character around the damaged compressor blades will lead to a change in the effectiveness of compression processes and compressor operation as a blade unit [11-16].

In accordance with the standards and manuals for designers at the stage of GTE designing, engineering documentation for the pilot item provides creation of blade damages’ allowances, at which GTE operation is allowed without limiting of the service life. Compressor blade damages’ allowances, operated as a blade unit, are not specified.

In operating conditions, this circumstance makes it difficult to estimate a decrease in the effectiveness for the damaged compressor operation and, particularly, in some cases it is rather difficult to determine the real cause of compressor surging, which happens in flight and is not reproduced during bench tests.

Therefore, with the purpose of CA flights safety improvement and effective aircraft GTE use, it is expedient to have the data not only pertinent to the effect of some types of compressor blades’ operational damages on a decrease in their structural strength, but the data on a possible change in the stable engine operation and a decrease in the compressor effectiveness as a blade unit as well.

2. PURPOSE AND OBJECTIVES
Research purpose: to ascertain the effect of some types of operational damages of compressor blades within the aircraft gas-turbine engine on the compressor characteristics and GTE performance.

Research objectives
- To develop an analytical model connecting some compressor characteristics with the extent of operational damages in the form of chipping at the leading edge of the compressor blade;
- Based on the analytical method, to estimate the effect of chippings at the leading edge of the aircraft GTE compressor blade on a change in the compressor characteristics;
Based on the CFD analysis, to estimate the effect of chippings at the leading edge of the aircraft GTE compressor blade and of plastic damages of the blades bodies on the GTE performance.

3. METHODS AND MATERIALS

In order to reach the research purpose, two methods have been used, namely:
- analytical method for estimation of relations between the characteristics of the compressor operating as a blade unit and the operational damages’ characteristics of compressor blades. This method is based on the use of principal analytical relationships established by the theory of blade units;
- simulation method pertinent to processes of compressor operation and air flow around the blade profile using gas dynamics numerical methods, which describe the gas flow with the least possible allowances, in other words, CFD analysis [17-22], aimed to estimate the damaged blade profile effect on the flow character and compressor characteristics. CFD analysis has been performed by Candidate of Science (Engineering) Fedechkin S.K., who has used commercial software.

In this study, chippings at the leading edge of the low-pressure compressor (LPC) blades, which were caused by FO strike, and plastic deformations of the blades bodies caused by the bird strike, have been considered as the primary operational damages of compressor blades (Figs. 1, 2). These deformations lead to a change in the blades’ configuration and of the angle of attack in the damaged area.

The principal factors, providing blades’ damage by the FO and bird strikes, are as follows: the shape, sizes and material of the FO, the speed and direction of their movement relative to the blade, as well as the material, sizes and shape of the blade itself. The geometrical parameters of the damaging objects, their materials and speeds of movement are rather different. In most cases, it is impossible to identify an object, which caused the damage of the blade. The collision velocity with the foreign object, in accordance with some estimates, is almost equal to flow tip speed. Compressor blades’ damages are generally represented by dents, chippings and cracks. Mostly they appear at the leading edge of a blade and are characterized by different forms and dimensions not exceeding several millimeters.

It is rather difficult to describe the processes of the blades’ damaging and of compressor and GTE effectiveness decreasing. This is due to difficulties arising during description of GTE components and interaction with FO or birds, as well as due to a variety of damaging objects, uncertainty of collision velocities with the blade and so on. Generally, such model may be presented as an assembly of interrelated and interacting elements of the system in terms of "Gray box". The output parameters in this model are corresponding to the research purpose. The principal elements of such a system are the GTE model, the FO model and the bird model.

The analysis of the factors leading to the engine failure through its damage by FO or by birds shows that the loss of function takes place in consequence of the following reasons:
- appearing of inadmissible damages of the design components in the LPC blading section under the damaging effect of FO or birds;
- choking of the blading section and the engine air systems by FO particles and by birds' remains;
• malfunction of the engine systems caused by entering into the engine channel of dust, birds' remains and solid fragments from the destroyed structural components.

The analysis of the GTE damage dynamics caused by the damaging effect of FO and birds has shown that the GTE damage is determined by the character of the system operation, among the elements of which are FO and birds, air flow, structural components of LPC blading, the properties of which are changed as the damage process advances. The interconnection and interaction of elements of this system with changing properties determine the character of GTE damage. Therefore, reliable determining of GTE damage caused by FO, birds and dust strike is possible only in the course of investigations of the damage process, with due account of interconnections and interactions of the system components determining the damage process.

Consequently, creation of a GTE, being FO and bird strike-proof, is possible provided it is realized with due account of the system components’ interconnection, which determines the process of FO and birds interaction with the GTE blading elements. Such GTE creation is based on understanding the mechanisms of the damage processes affecting the compressor operation effectiveness, as well as of GTE operation effectiveness decreasing with due account of special features of their designs, technology and operational factors.

If during operation, the compressor rotor blade will be damaged, then the damaged compressor should be repaired in accordance with the restoring technology developed for each specific type of aircraft GTE. It is supposed that repairing damages will allow eliminating or reducing the negative effect of compressor blades damage on the safety of GTE use.

Blades’ repair through cutting-down makes it possible to reduce stress concentration and to restore the configuration of the repaired blade profile close to the design profile of the undamaged blade. However, to reach such a result in practice is impossible. Therefore, the geometrical dimensions of the restored blade differ from the geometrical dimensions of the design blade. Consequently, the actual flow does not get in line with the design flow, which leads to vortex flows generation, additional hydraulic losses, a reduction in the of compressor gas-dynamic stall margin and a decrease in the GTE use effectiveness. Such characteristic as fuel consumption is substantially changed.

Damages regulation is aimed exclusively to provide fatigue strength characteristics in terms of allowable chippings. Allowable chippings, plastic deformations and areas of their location on the blade's body are generally determined based on the principle of fatigue strength assurance within the limits of the design fatigue life (durability). It is accepted that the blades with the allowable chippings do not exert substantial effect on the compressor gas-dynamic characteristics and, respectively, on the safety and effectiveness of GTE use. The rating of damages affecting the compressor as a blade unit is not specified in these documents. Therefore, the estimation of the effect exerted by operational damages, by changes in the blade profiles’ configuration caused by their damage and by changes in the repaired blade profile configuration on the compressor gas-dynamic characteristics and the safety and effectiveness of GTE use is not included into operational documentation. However, the practice of GTE operation indicates the necessity to have such data.

The simulation of the damage extent for the compressor rotor blades was based on the model of a four-stage LPC within a bypass turbofan engine (TFE), which was used as the design model in CFD analysis (Fig. 3).
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**Figure 1** Compressor rotor blades’ deformation schemes in the form of downturn and bend of the blade body under the bird strike, accepted for numerical simulation of processes in the compressor; stages: (a) the blade is not damaged; (b) plastic deformation of the blade in the form of downturn of the top body part; (c) plastic deformation of the blade in the form of the body bend.

**Figure 2** Models of undamaged (a) and damaged (b) compressor rotor blades accepted for numerical simulation of processes in the compressor; $h$ – blade height; $b$ – chord.

**Figure 3** Model of a low-pressure compressor of a turbofan engine.
The model was developed with due account of the necessity:
- to calculate compressor characteristics with both undamaged and damaged rotor blades;
- to determine the character of flow around the damaged blades depending on the type of
damage, the area of damage location on the blade body, the quantity of damages on the blade
body and on compressor rotor wheel.

ACFD simulation of compressor operation processes, and a study of the damaged blade
profile effect on the flow character and compressor characteristics have been fulfilled with
observance of the basic principles of the working medium mass flow ratio changing,
parameters changing at the boundaries of adjacent design areas using numerical gas-dynamic
methods, describing gas flow with the least possible allowances [17-22].

A numerical simulation of the compressor operating process made it possible:
- to determine all flow characteristics at all points of the design area;
- to take into consideration the effect of all operational damages on the compressor
characteristics;
- to plot the curve corresponding to operating regimes with due account of compressor
characteristics with the damaged blades.

The results of plotting the curve corresponding to operating regimes, which have been
obtained within CFD analysis, are presented in fig. 5.

A change in the compressor gas-dynamic stall margin with the damaged rotor blades was
estimated through a change in the parameter

$$DK_{st} = \frac{p_{bor}^{*}G_{air.m.s.bor}}{p_{c.l.o.m.f.}^{*}G_{m.l.o.m.f.}} - 100\%.$$  

$$p_{bor}^{*}, G_{air.m.s.bor}$$ - compression ratio and corrected compressor air flow rate at the border
of the stable operation at appropriate rpm respectively.

$$p_{c.l.o.m.f.}^{*}, G_{m.l.o.m.f.}$$ - compression ratio and corrected compressor air flow rate at
performance envelope at appropriate rpm respectively.

The values of $$p_{c.o.m.}^{*}$$ and $$G_{air.m.o.m.}$$ were determined in accordance with the operating
regimes curve.

4. RESULTS AND DISCUSSION
A change in the profiles’ configuration of the compressor damaged rotor blades occurs in
consequence of profile chord decreasing; a change in the angle of attack; a change in the
leading edge radius of the blade; profile changing in consequence of local plastic deformation
(downturn, angle breach, dents and others); a change in the surface area of the blade body. A
change in the profiles’ configuration of the compressor damaged rotor blades leads to a
change in the angle of attack.

From the analysis of the results of the blades’ damage in the form of chipping, it follows
that while the angle of gas flow at louver input, $$\beta_{1}$$, is not changed after the damage of
the blade body, the chipping at the leading edge facilitates appearance of the additional angle of
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attack $\Delta a = b_{lb.ch} - b_{lb}$, where $b_{lb.ch}$ is the design angle at the profile input, formed by the line tangent to the centerline of the profile in the blade's damage point in the form of chipping and louver front; $b_{lb}$ –is the design angle at profile input, formed by the line tangent to the centerline of the undamaged blade profile and louver front. The sign of the additional angle of attack $\Delta a$ is formed depending on the damage character (chipping, chipping with plastic deformation and so on).

If plastic deformations at the boundary between the surface of the blade body and the surface of the chipping are absent, then a positive additional angle of attack is formed. If plastic deformations at the boundary between the surface of the blade body and the surface of the chipping are present, then the sign of the angle of attack is formed depending on character of the plastic deformations and may be not only positive but also negative.

A change in the blade profiles’ configuration leads to deterioration of their structural strength and a change in the flow character around the damaged blades’ profile being an object located within the air flow. The deterioration of the flow character around the compressor blades leads to a change in the air consumption in the adjacent blade passages. The velocity at the output from the blade passage is decreased. In channels adjacent to the channel with the damaged blade, air consumption is either increased or decreased depending on an increase or decrease in the angle of attack. Rotating stall may be formed, which leads to a decrease in the effectiveness of the whole blade row with the damaged blade in the form of chipping caused by an increase in the angles of attack.

A change in the working medium flow character around the damaged blades’ profile relative to the design flow around the undamaged blades facilitates a change in the flow structure; vortex flows’ generation; appearance of velocity and pressure profiles’ irregularities behind the rotor wheel and behind the deflector in radial and circular directions; a change in the air consumption in blade passages with the undamaged blades within the damaged cascade; deterioration of the intake (suction) capacity of the damaged profile; velocity decreasing at the output from the blade passage; deterioration of some other characteristics of the operational process.

Changes in the flow structure facilitate a decrease in the compression process effectiveness and a decrease in the effectiveness of the whole blade row, as well as a decrease in the compressor stage stall margin and compressor operation in general. A decrease in the compressor effectiveness and compressor gas-dynamic stall margin caused by the blades’ damage leads to a reduction in the aircraft safety factor and facilitates an increase in the operational expenses connected with the necessity to provide additional conditions of the safe operation and restoring of the damaged GTE.

The results of analytical estimation of effect of the compressor blades’ damage on a change in its characteristics are as follows.

A change in the air consumption in the blade passage of the operational louver of the basic cascade, formed between $i$ and $i+1$ sections and two adjacent profiles, in case of the blades' leading edge damage in the form of chipping, is characterized by the following equation:

$$ G_k - DG_k = (c_{i+1} - c_{i}) (F_k + DF_k) r_k, $$

(1)
where: $G_k$ – is the air consumption through blade passage of the operational louver of the basic cascade between $i$ and $i+1$ sections with the undamaged blade; $DG_k$ – is the change in the air consumption through the blade passage between $i$ and $i+1$ sections caused by the blade damage in the form of chipping; $Dc_{lu}$ – is the change in the velocity consumption constituent between $i$ and $i+1$ sections in front of the wheel in the blade passage of the operational louver of the basic cascade caused by the blade damage in the form of chipping; $c_{lu}$ – is the velocity consumption constituent between $i$ and $i+1$ sections in front of the wheel in the blade passage of the operational louver of the basic cascade with the undamaged blade; $DF_k$ – is the change in the open flow area for air in the blade passage of the operational louver of the basic cascade between $i$ and $i+1$ sections caused by the blade damage in the form of chipping.

If $G_k = c_{lu} F_k r$ and $DG_k = Dc_{lu} DF_k r$, then from equation (1) it follows that

$$Dc_{lu} = \frac{c_{lu} DF}{F_k}$$

(2)

In other words, damages of the blades’ leading edge in the form of chipping facilitate a change in the velocity consumption constituent by the value of $Dc_{lu}$, which is determined by the damage extent $DF_k$ and by the value of the velocity consumption constituent $c_{lu}$ in front of the wheel, before the blade damage.

A change in the $DF_k$ is determined by a decrease in the operational profile chord, which, in turn, is determined by the depth of chipping, by a change in the blade profile configuration and by the compressor and GTE design.

Since the $c_{lu}$ value depends on the GTE operating mode, it means that the effect, exerted by the compressor blade damage on the effectiveness of its operation as a blade unit will be determined not only by the chipping depth and compressor design, but also by the GTE operating mode. This fact is confirmed by the results of numerical simulation.

The simulation of the flow around the damaged blade profile using computational fluid dynamics (CFD) software made it possible to ascertain the following principles of the compressor characteristics’ alteration depending on the damage extent.

The damage of the leading edges of the blades in one local area leads to a change in the flow character around the damaged blade without disturbance of the flow character around the adjacent undamaged blades (Fig. 4). The blades’ damages in several areas along the height lead to creation of local stalling zones in these damaged areas, which differ by value depending on the damage extent and location of the damage.
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Figure 4 Flow character around the LPC blades; the blades’ damage in the form of 6 mm depth chipping

The damage of the leading edges of the LPC 1st stage rotor wheel blades within the TFE in two local areas will change the flow character around the blades in the zones of their damage, which depends on the location of these zones along the height of the blade.

For the isolated 1st stage rotor wheel of the studied four-stage LPC, 50% blades of which are damaged in the form of single chipping, characterized by the depth of \( z_b = 6.0 \) mm, located on the leading edge at \( l = 0.3h \), in case of a specific mode of GTE operation gas-dynamic stall margin may be reduced from 17% up to 13%.

The substantial deterioration of the characteristics \( p^* = f(n_{m}, G_{\text{air}, m}) \) and \( p^* = f(n_{m}, h^*) \) of the four-stage LPC with the damaged blades occurs in a certain range of LPC rotor speeds (rpm), however, only in case of substantial damages of the blades’ leading edges in the form of chippings. The most significant changes were registered for damages in the form of chippings having the depth of \( z_b > 6.0 \) mm and for \( n_{m} \gg n_2 \) mode of operation (Figs. 5, 6). For the studied LPC model, chippings with the depth of not more than 0.5 mm are allowed without their cutting-down, and those having the depth of not more than 2.0 mm are allowed after cutting-down of such chippings.

If up to 50% of rotor blades of the isolated (without stator) rotor wheel are damaged and have two chippings with the depth of \( z_b = 6.0 \) mm in the areas of \( l = 0.3h \) and \( l = 0.7h \), then the gas-dynamic stall margin may be reduced from 17% to 9%. The damaged rotor wheel, considered together with stator, exerts more substantial effect on the deterioration of characteristics than the isolated damaged rotor wheel.

A zero change of the gas-dynamic stall margin \( D K_D \) for compressor with the damaged rotor blades in case of other modes of GTE operation may be realized due to mutual compensation of the changing parameters \( p^*_c \) and \( G_{\text{air}, m} \).
Figure 5 Characteristic curve $p^* = f(n_m, \bar{G}_{air,m})$ for the four-stage LPC depending on the damage extent ($z_b$), the area of its location ($l$), the quantity of the damaged blades ($N$).

Figure 6 Changes in characteristic curve $p^* = f(n_m, \bar{G}_{air,m})$ for the four-stage LPC depending on the plastic deformation extent of the rotor wheel blade body.

The received data show that the operational damages of compressor blades exert the most significant effect on a change in the compressor characteristics only for a certain mode of GTE operation. For other modes, the effect of damages is negligible and may be ignored as a factor exerting substantial effect on the effectiveness of the compressor operation as a blade unit.

Chippings’ cutting-down and removal of definite zones of plastic deformations make it possible partly to compensate a decrease in the fatigue strength of blades; however, these procedures do not solve the problem of the damages’ effect on a change in the effectiveness of GTE use with the repaired compressor blades.

Accordingly, safe GTE operation and providing of the required safety level of aircraft flights may be reached only based on the data analysis pertinent to joint estimations of effect exerted by compressor blades’ damages, both in terms of strength and in terms of the effect of the damaged compressor blades on a possible decrease in its operation as a blade unit.
The estimation of the effect of operational damages of compressor rotor blades on a change in the GTE technical state and the compressor characteristics may be realized based on the following approach.

Let the assumption be valid that the generation of \( S(t) \) state of GTE may be represented as the sum of the constituent states, generated by \( Z \) action and degradation (deterioration). Then the following equation will be valid:

\[
DS_{j \text{im}}(t) = DS_{j \text{im}}^{Z}(t) + DS_{j \text{im}}^{D}(t),
\]

where: \( DS_{j \text{im}}^{Z}(t) \) – is the change in the technical state of the \( j \)-th element of the \( i \)-th GTE module caused by external damaging factors and degradation;

\( DS_{j \text{im}}^{Z}(t) \) – is the change in the technical state of the \( j \)-th element of the \( i \)-th GTE module caused by external damaging factors;

\( DS_{j \text{im}}^{D}(t) \) – is the change in the technical state of the \( j \)-th element of the \( i \)-th GTE module caused by degradation.

For GTE in general, the following equation will be valid:

\[
DS(t) = DS^{Z}(t) + DS^{D}(t),
\]

where: \( DS^{Z}(t) \) – is the change in the GTE technical state caused by external factors \( Z \), which is characterized by the difference between the values of input parameters, in case of zero affecting external factors, and the values of output parameters during monitoring (diagnostics), in case of affecting external factors.

\( DS^{D}(t) \) – is the change in the GTE technical state caused by degradation, which is characterized by the difference between the values of output parameters, determining the technical state in operational condition, and the values of output parameters during monitoring (diagnostics), in case of zero affecting external factors.

Further, if there exists \( DS(t) \) caused by the effect of damaging factors \( Z \) on GTE, then it becomes possible to determine the reason of technical state changing.

If during estimation of GTE technical state, the distinction between a change in the technical state caused by degradation, \( DS^{D}(t) \), and a change in the technical state caused by external factors, \( DS^{Z}(t) \), are not taken into account, then such an approach may lead to difficulties in establishing the real reason of technical state changing.

For GTE, the assumption is valid that GTE may be considered as the object of a "black box" type, characterized by a set \( Z(t) \), a set of control actions \( U(t) \) and a set of output parameters \( Y(t) \), the elements of which, \( y(t) \), are determined by the GTE state and by the control actions' values. Then the model, characterizing a change in the GTE state as an operational object, may be presented as follows:
\[ M_{\text{stan}} = \{T, U, Z, Y, W_u, G\}, \]

where: \( T = \{t_1, t_2, \ldots, t_i, \ldots, t_r\} \) – is the ordered finite set of time points, at which the values of parameters of the set elements \( Y(t) \) and \( Z(t) \) have been measured;

\( U(t) \) – is a set of input control actions;

\( Z(t) \) – is a set of external affecting factors;

\( Y(t) \) – is a set of output parameters;

\( W_u \) – is the space of \( u(t) \) functions describing allowable input exposures;

\( \Gamma \) – is the space of \( y(t) \) functions describing a change in the output parameters in time.

The explicit parameters of the GTE technical state \( S(t) \) are not presented in this model. However, the changes of \( S(t) \) exert an effect on the character and sequence of the control actions for compensation of disturbing factors exerting an effect on the GTE operation as an operational object. In this case, \( S(t) \) is considered as the state generated under the effect of the external affecting factors and degradation, and is determined by a finite set consisting of \( K \) elements, \( S(t) = \{S_1, \ldots, S_k, \ldots, S_K\} \),

where: \( S_k \) – is the actual \( k \)-th GTE technical state, generated during operation under effect of real external affecting factors \( Z^k_t \).

Then estimation of operation quality, depending on the GTE technical state, may be performed using the following algorithm:

1. If

\[ \text{DY} \left( t_i \right) = Y \left( t_i \right) - Y_{\text{max}} \left( t_i \right) \leq 0, \]

\[ \text{DY} \left( t_i \right) = Y \left( t_i \right) - Y_{\text{min}} \left( t_i \right) \geq 0, \]

then GTE is functionally operative.

Here \( Y_{\text{max}} \left( t_i \right) \) and \( Y_{\text{min}} \left( t_i \right) \) – are the maximum and minimum allowable values of the output parameter, respectively.

2. If

\[ \text{DY} \left( t_i \right) = \left| Y \left( t_i \right) - Y_{\text{ref}} \left( t_i \right) \right| > \text{DY}_{\text{TU}} \left( t_i \right), \]

then technical state within the normal operation area has deteriorated during operation.

Here: \( Y_{\text{stan}} \left( t_i \right) \) – is the output parameter value following the reference standard;
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\( D Y_{TU}(t_i) \) – is the maximum allowable deviation of the output parameter value from the reference standard value.

3. If

\[
DY(t_i) = \left| Y(t_i) - Y_{\text{stan}}(t_i) \right| \leq D Y_{TU}(t_i),
\]

then the GTE technical state has not changed during operation.

The algorithm was generated based on the condition that the GTE operation model was presented as "input – output" of the "black box" \( \mathcal{M}_{\text{stan}} = (T, U, Z, Y, W_u, G) \).

In GTE model, only output parameters \( Y(t) \) are compared with a set of allowable values pursuant to specification. Therefore, this model reflects the real process of technical state changing caused by the affecting factors not in full scope.

The superior model of GTE technical state changing \( \mathcal{M}_{\text{tsGTE}} \), which takes into account the real process of technical state changing, may be presented as the "input – state – output" model in the form of a finite sequence

\[
\mathcal{M}_{\text{tsGTE}} = (T, U(t), Z(t), Y(t), S(t), W_u, G y, j),
\]

where: \( Z(t) = \{z_1(t), z_2(t), \ldots z_p(t), \ldots, z_p(t), \} \) – is a finite set of the affecting factors, \( p = 1, 2, \ldots, P \) of various nature

\( S(t) = \{S_1(t), S_2(t), \ldots S_k(t), \ldots, S_k(t)\} \) – is a finite set of the technical states, \( k = 1, 2, \ldots, K \);

\( y : Z \circ S \) – is the transient function characterizing the consistent pattern of a change in the elements of the set of states, \( S(t) \), caused by input affecting factors, \( Z(t) \), and determined by initial state, \( S_0(t) \). For each input affecting factor \( z \in Z \), the function \( y \) determines the GTE state as an element of the set \( S(t) \) in the form of \( y(z) \in S(t) \);

\( f : Z \circ S \circ Y \) – is the output function characterizing the consistent pattern of generation of a set of output elements, \( Y \), caused by input affecting factors, \( Z \), and determined by the initial state, \( S(t) \). Here for each \( y(z) \in S(t) \), the function \( f \) determines the set element \( Y \) as \( f(y(z)) \in Y \).

"Input – state – output" model, \( \mathcal{M}_{\text{tsGTE}} \), allows determining GTE behavior depending on its technical state and estimating the consistent pattern of a change in the elements of the set of states, \( S(t) \).

The patterns of \( y : Z \circ S \) and \( f : Z \circ S \circ Y \) functions play the primary role in this model. These functions (\( y \) and \( f \)) adequately reflect the actual processes pertinent to the
technical state changing, provided they take into account the real operation conditions and actual state of operating component. Therefore, simulation and development of methods should be performed with due account of the real operation conditions and actual state of operating component.

Changing GTE technical state caused by external affecting factors and degradation is characterized by a change in the output parameters’ values in the space of these parameters. The function \( y' : Z \otimes S \) determines the consistent pattern of a change in the elements of the set \( S(t) \) caused by input affecting factors \( Z(t) \). The function \( f : Z' \otimes S \otimes Y \) characterizes the consistent pattern of the generation of elements of the set of outputs \( Y \) under effect of the input affecting factors \( Z \) and state parameters \( S(t) \). These functions determine the consistent pattern of GTE technical state changing.

Thus, generation of GTE technical state under external affecting factors and degradation is determined by the patterns of \( y \) and \( f \) functions depending on the operating factors. During estimation of reliability of the created mathematical model describing a change in the GTE technical state, reproducibility of the developed model in different experimental and practical operational conditions has been revealed and qualitative coincidence of the results obtained by the authors of this article with the results presented in independent publications devoted to this topic [23-26] has been found.

5. CONCLUSIONS
The results of the performed investigation reflect an interest of experts involved in practical aircraft GTE operation in data, pertinent to character of the operational damages of the compressor blades during compressor operation as a blade unit. The performed numerical simulation of the compressor operation with the damaged blades has shown that the obtained simulation results agree well with the results of the GTE operation in real conditions.

The analytical estimation of the compressor blade operational damages’ effect on its parameters as a blade unit has shown that the principal parameters exerting an effect on a change in the consumption constituent of the flow velocity at its input into the compressor stage, in case of the blades’ damage, are the value of the consumption constituent of the flow velocity in front of the rotor wheel before the blades’ damage, mode of operation and the damage extent.

A change in the compressor characteristics in case of the damaged blades facilitates a change in the GTE technical state, the level of its operating capacity and evidences on the fact that the damaged blades exert an effect on the compressor, being the blade unit, depending on the compressor design, GTE design and mode of its operation.

The results of numerical simulation have shown that the compressor blades’ damages exert the most substantial effect on a change in the compressor characteristics only for the case of a certain mode of GTE operation, while for other modes effect of damages is negligible and should not be considered as the factor exerting an effect on the effectiveness of the compressor operation as a blade unit.

The performed numerical simulation of the effect of the compressor rotor blades’ damages on the compressor operation as a blade unit has shown that the simulation results based on the accepted analytical model agree well with the actual physical processes and concepts. The simulation results also agree well with the results of analytical investigations, in which the
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suggested model of consumption constituent changing depending on rotor blades damage has been used.

The results of investigations have shown that it is appropriate to perform estimation of effect of the compressor blades’ damages in an integrated manner, both with due account of a decrease in the fatigue strength of the damaged blades, and with due account of the compressor blade damages’ effect on a decrease in the effectiveness of the compressor operation as a blade unit, on a change in the fuel consumption and effectiveness of GTE use.

It is appropriate to perform such estimation at the stage of GTE creation. The estimation of the compressor characteristics with the damaged blades at the stage of GTE creation will make it possible to manufacture more reliable and effective GTEs, and during operation to use the endurance capabilities of aircraft GTEs more safely and effectively and to forecast a change in the compressor characteristics under effect of the operational damaging factors. If during operation, the task will appear to determine the reasons of GTE unstable operation, then usage of numerical simulation of compressor operation with the damaged blades will allow shortening the terms of investigations aimed to determine the reasons of GTE unstable operation and improving the quality of investigation.

The estimation of the effect of the operational damages of compressor rotor blades on a change in the GTE technical state and on a change in the compressor characteristics may be realized based on the following approach.

Let the assumption be valid that the generation of the \( S(t) \) state of GTE may be presented as a sum of states of the constituent components, modules, structural elements, generated by the affecting factors \( Z \) and in consequence of degradation.

Further, if estimations of changes in the GTE technical state, \( DS(t) \), and estimations of changes in the GTE technical state caused by damaging factors, \( Z \), are available, then it is quite possible to determine the reason of technical state changing in the operational capability area and to estimate the GTE performance and technical state with particular detailing following the respective algorithm. The algorithm is developed on the basis of the assumption that the GTE operation model is represented by the "black box", as "input – output".

The model of a change in the GTE technical state, in which the GTE is considered as an operational and diagnostics object, may be presented as the "input – state – output" model, which allows explaining the observed behavior of the GTE depending on its technical state and to estimate the consistent pattern of a change in the elements of the set of states.

REFERENCES


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