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# INFLUENCE OF GAS TURBINE ENGINE GAS-AIR CHANNEL OPERATIONAL FACTORS AND DAMAGEABILITY ON ITS COMPONENTS PERFORMANCES

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*This paper deals with the gas-air channel geometry modification, during service life, and its influence on gas turbine engines components performance. Functional relations between gas turbine engine components parameters and run hours are presented.*

## Introduction

Deviation of gas turbine engine (GTE) components characteristics from the designed values may be caused by industrial imperfections and operation factors.

Some operation factors directly influence GTE components characteristics, for example: Reynold's number deviation, inlet distortion, unstable flow at transient modes and during input disturbances, change of ambient air humidity, overheating, tropical precipitation, clouds and so on.

Factors connected with presence of dust and chemically active substances in the atmosphere, foreign objects getting inside during taxiing influence GTE components characteristics indirectly, that is the listed factors cause gas-air channel damage (gas-air channel geometry is changed). Long-term presence of these factors changes GTE components characteristics while in service. It leads to lowering compressor and turbine efficiency, increased losses in all units.

## Analysis of research works and publications

Quantitative estimation methods of some mentioned above operational factors influencing turbine engine components performances are presented in [1–3]. For example, in [1] some approaches are considered for quantitative estimation of compressor blades damage influence on its efficiency and pressure ratio.

For practical application of this approach it is necessary to determine the type and value of blade damage with the help of a testing system (baroscope, coordination devices and computer). For this purpose we determine dents size and value of blades strain at each stage, and then, on the basis of mathematical relations, we can determine compressor efficiency $\delta\eta_c^*$ and pressure ratio $\delta\pi_c$ modification. In case of dents presence, compressor stage efficiency deviation is determined by the following formula as offered in [1]:

$$\delta\eta_s = \left(1 - \frac{\eta_{sd}}{\eta_{so}}\right)\frac{Ln_{bd}}{hn_b},$$

where $\eta_{sd}$ is local decrease of stage efficiency; $\eta_{so}$ is initial stage efficiency; $L$ is dent length; $n_{bd}$, $n_b$ are number of damaged blades and number of blades, respectively; $h$ is dent depth.

Interaction of relative stage efficiency deviation and relative change of pressure ratio with assumption of compressor stage continuous work is described by an equation:

$$\delta\pi_s = \frac{1}{A_1}\delta\eta_s;$$

$$A_1 = \frac{\pi_s^{\frac{\gamma-1}{\gamma}}}{\left(\pi_s^{\frac{\gamma-1}{\gamma}} - 1\right)}\frac{\gamma - 1}{\gamma},$$

where $\gamma$ is specific heats ratio.

Pressure ratio change at multistage compressor equals:

$$\delta\pi_c = \delta\pi_{s1} + \sum_2^i \delta\pi_{si},$$

where $i$ is number of stages.

Authors of [1] obtained an equation for the case of compressor blades strain. This equation links the value of working wheel outflow angle deviation and relative pressure ratio change in a stage, that are caused by a strain of profiles (profiles displacement relatively to initial position).

The deficiency of the method offered for quantitative estimation of gas-air channel imperfections influence on compressor performance is the necessity of test bench experiments. Conduction of expensive bench trials of compressors and their stages with characteristic imperfections of gas-air channel operation conditions is crucial for this method.

The similar method is offered in [2] for determination of efficiency and pressure decline value in the turbine with modification of nozzle box area and radial gaps while in service.

The deficiency of the method [2] is the necessity of sequential calculation of each consequent stage kinematical parameters taking into account the changes of previous stage velocity diagrams in a multistage turbine.

In [4] compressor performances deviation contemplating methods are considered for the case of inlet distortion, increase of humidity and Reynold's number.

However the generalized relation of Reynold's number influence on efficiency and pressure ratio for all compressors types has not been obtained so far. On the basis of operational research [5] the authors established, that for a particular compressor design Reynold's number influence on efficiency is described by the following relation:

$$\overline{\eta}_c = a_0 + a_1(\overline{R}_e) + a_2(\overline{R}_e^2) + a_3(\overline{R}_e^3);$$

$$\overline{\eta}_c = \frac{\eta_c}{\eta_{co}},$$

where $\eta_{co}$ is value of efficiency if $R_e > 3{,}5 \cdot 10^5$;

$\overline{R}_e = \frac{R_e}{10^5}$; $a_0, a_1, a_2, a_3$ are constants.

Thus values of factors $a_0 \ldots a_3$ will be different for different rotational speeds of compressor rotor. For some compressor designs after $R_e$ decrease from $3{,}5 \cdot 10^5$ to $10^5$ efficiency decreases by 4–5 %.

The non-stationary phenomena connected with throttle lever moving or aircraft evolutions, change compressors characteristics greater than those of other components [6]. Change of air parameters occurs in compressor during unsteady modes as compared with steady ones owing to independent influence of:

– air inertia moment with its local speed change at stages;

– inequality of air consumption at various cross-sections;

– delays of air parameters change at subsequent stages because of final speed of distortion distribution along a flow.

Total parameters change is determined as a sum of all changes caused by listed factors.

Non-stationary characteristics of compressors (figure) differ from the stationary ones. The direction of stability border and head curves displacement is defined by transient process character (gas reduction or acceleration).

Position of compressor non-stationary characteristic head curve is determined by following coordinates:

$$[(\pi_{c.0} \pm \Delta\pi_c), (\dot{m}_a \pm \Delta\dot{m}_{a.in})],$$

where $\Delta\pi_c$ is total change of $\pi_c$:

$$\Delta\pi_c = \Delta\pi_{c.in} + \Delta\pi_{c.m};$$

$\Delta\pi_{c.in}$ is change of pressure rise due to air flow inertia moment and delay of parameters change along the gas-air channel; $\Delta\pi_{c.m}$ is change of $\pi_c$ caused by inequality of air consumption along compressor gas-air channel:

$$\Delta\pi_{c.m} = \frac{1}{2}\left(\frac{\partial\pi_c}{\partial\dot{m}_a}\right)_n \Delta\dot{m}_{a.in};$$

$\Delta\dot{m}_{a.in}$ is reduction or increase of air mass contained between compressor entrance sections and an exit from it:

$$\Delta\dot{m}_{a.in} = \frac{1}{2}\frac{M_c}{\gamma p_c}\frac{dp_c}{dt};$$

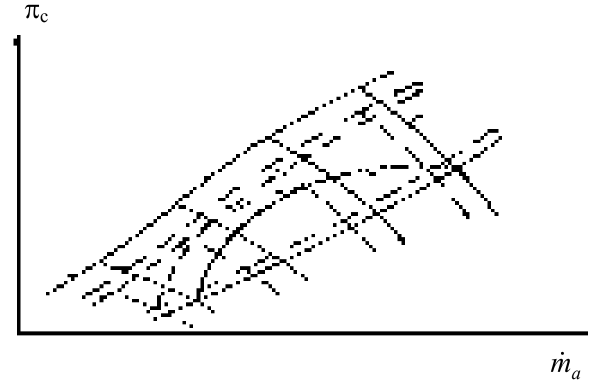
$M_c$ is mass of air contained in compressor; $\dot{m}_a$ is compressor mass flow rate; $\gamma$ is specific heats ratio; $\frac{dp_c}{dt}$ is change, in time, of pressure behind compressor.

The sign "+" in this case corresponds to gas reduction, and the sign "–" to acceleration.

Partial derivative

$$\left(\frac{\partial\pi_c}{\partial\dot{m}}\right)_n = \text{const}$$

is taken from the known steady axisymmetric compressor characteristic at the point corresponding to considered instant transient mode. Thus we assume, that around the considered point, compressor transient mode characteristic head curves are equally distanced from the head curves of compressor stationary characteristic.



Compressor characteristics

## Problem statement

Deviations of compressor and turbine efficiency, factor of full pressure preservation in combustion chamber and passage cross-sections of turbine nozzle box and jet nozzle change not only key parameters of engine, but in their turn, influence service life time and reliability of the engine as well. So, for example, gas temperature in front of turbine increases owing to change of loss factors. Engine power falls, that worsens aircraft characteristics.

Analysis of existing methods of GTE components changed characteristics estimation under the influence of operational factors has shown, that for given types of engines, complex methods have not been developed, so far.

Those methods would allow us to estimate all changes of components parameters (compressor and turbine efficiency, factors of full pressure preservation in input and output devices, as well as the areas of nozzle boxes passage cross-sections of turbine and jet nozzle).

The above confirms the necessity of developing complex methods for estimating components characteristics modifications, losses factors and channels cross-sections areas while in service. And we must also create GTE diagnostic models allowing, with the help of measured parameters and actual components characteristics, to determine key parameters (thrust or power, specific fuel consumption, gas temperature at turbine inlet section).

## Changed characteristics estimation methods

The authors offer, depending on GTE controllability level, two approaches to estimate components characteristics changes and key engine parameters during service life.

For engines with low controllability level, having a lot of run hours, the following is offered: with help of data received during failure diagnostics at engines repair time, using methods of one and multifactor analysis, we establish relations between GTE components parameters and service hours. Then linear or non-linear model of an engine working process can be used to determine its key parameters.

So, for example, for AI-24 turbo-prop engine the authors have received regress equations, allowing to describe dependence of compressor and turbine efficiency, as well as the blade channel area of turbine first stage nozzle box on service time:

$$\eta_C^* = 0{,}6742+0{,}176493\cdot 10^{-5}\,\tau – 0{,}221473\cdot 10^{-9}\,\tau^2; \quad (1)$$

$$\eta_T^* = 0{,}7036+0{,}188694\cdot 10^{-5}\tau – 0{,}219605\cdot 10^{-9}\tau^2; \quad (2)$$

$$A=246455{,}74–12151854\lg\tau+16326{,}715(\lg\tau)^2. \quad (3)$$

To determine full pressure preservation factor change in combustion chamber, the results of long bench tests of twelve engines with a similar combustion chamber design were used. As a result of mathematical processing of the data received following functional relation between full pressure preservation factor deviation and engine run hours was established:

$$\delta\sigma = 0{,}1069 + 0{,}0172(\bar{\tau}) - 1{,}2931(\bar{\tau})^{1/2}; \quad (4)$$

$$\bar{\tau} = \frac{\tau}{\tau_p},$$

where $\tau_p$ is engine service life.

Another approach can be used for modern engines with high controllability level. The essence of the second method consists in determination of damages amount. For example, during compressor survey a baroscope is used, then with the help of techniques shown in [7; 8] we can determine compressor efficiency.

Losses caused by increase of relative turbine blade roughness and by blade channel cross-sections area modification can be determined by the formula given in [9]:

$$\xi_{roug} = (1{,}05...0{,}08)\varepsilon^{0{,}25}(C/S),$$

where $\xi_{roug}$ is losses factor; ε is relative roughness of blade surface:

$$\varepsilon = \frac{k}{c};$$

$k$ is average height of roughness ledges; $c$ is chord; $S$ is width of blades channel minimal cross-section.

Relative roughness and width of blade channel minimal cross-section can be determined during turbine check by modern baroscopes.

Actual value of turbine stage efficiency can be determined by the following formula:

$$\eta_t = \eta_{t_0} - \Delta\xi_{roug},$$

where $\eta_{t_0}$ is designed efficiency of turbine stage; $\Delta\xi_{roug}$ is losses factor change:

$$\Delta\xi_{roug} = \xi_{roug} - \xi_{roug_0}.$$

After actual value determination of engine components efficiency, full pressure preservation factors, turbine nozzle box channels cross-sections and jet nozzle areas by one of the listed methods; their mathematical models are used for engines key parameters determination. Authors, in particular, used a GTE mathematical model that consists of three groups of equations. The first group includes equations of propulsive mass balance charge at compressor and turbine.

Equations of power balances, that make the second group, look like:

$$\omega_{T.j}\left(\dot{m}_{j+1} + \Delta\dot{m}_j\right)\eta_{m.j} - \omega_{cj}\dot{m}_{cj} - \Delta\dot{w}_j = 0 ,$$

where $j$ is index for parameters of $j$ cascade of compressor and its turbine; $\Delta\dot{m}_j$ is air consumption for cooling turbine $j$ cascade blades; $\omega_{T.j}$, $\omega_{c.j}$ are work of turbine $j$ cascade and compressor, accordingly; $\Delta\dot{w}_j$ is power taken from $j$ cascade; $\eta_{m.j}$ is mechanical efficiency of $j$ cascade.

The third group consists of equations connecting parameters of working process and engine key parameters.

After determination of efficiency and losses factors deviations, linear model of an engine including the following system of equations can be used:

$$\delta P_j = \sum_1^m a_{ji}\delta\eta_i + \sum_1^m b_{ji}\delta\sigma_i + \sum_1^m d_{ji}\delta A_i ,$$

where $\delta P_j$ is deviation of single engine parameter (thrust, specific fuel consumption and gas temperature in front of the turbine) from designed values; $a_{ji}$, $b_{ji}$, $d_{ji}$ are constants of interference factors for given engine; $j$=1,2,3… is serial number of parameter; $i$=1,2,3… is serial number of losses factor. It is necessary to note that for each particular engine the character of geometry change differs qualitatively and quantitatively.

## Conclusion

The approaches offered for determination of actual values of compressors and turbines cascades efficiency, full pressure preservation factors, as well as areas of nozzle box channels cross-sections of engines with various controllability levels enable us to estimate their technical condition. And use of mathematical models in combination with offered techniques of components characteristics change estimation allows to determine actual values of engine key parameters (thrust, specific fuel consumption and gas temperature in front of the turbine), that is important for ensuring flight safety.

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Вплив експлуатаційних факторів і пошкоджуваності проточної частини газотурбінного двигуна на характеристики його елементів

Показано, як змінення проточної частини впливають на характеристики елементів газотурбінного двигуна під час експлуатації. Наведено функціональні залежності параметрів елементів газотурбінного двигуна від кількості часів роботи.

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Влияние эксплуатационных факторов и повреждаемости проточной части газотурбинного двигателя на характеристики его элементов

Показано, как изменения проточной части влияют на характеристики элементов газотурбинного двигателя в процессе эксплуатации. Приведены функциональные зависимости параметров элементов газотурбинного двигателя от величины наработки.