Optimization of a Single-stage Air Starter Turbine

Grigorii Popov[a], Oleg Baturin, Vasilii Zubanov[b], Daria Kolmakova[c], Anastasia Korneeva and Andrei Volkov

Samara National Research University, Samara, Russia

Keywords: Auxiliary Power Unit, Air Turbine, Optimization, Joint Operation, Gas Turbine Engine, Start-up Time, Torque.

Abstract: The paper describes the process of optimizing the blades of a starter air turbine for a gas turbine engine launch system. This task was initiated by the necessity to use an existing turbine when starting a new engine. During the study, it was found that the turbine, although it ensures the conditions for the joint operation with the auxiliary power unit turbine and meet the strength constraints, it does not allow to start the engine within the required time. As a result of studies using mathematical optimization methods involving commercial programs, a variant was found to modernize the baseline turbine, which provides an acceptable value of torque on the shaft with an adequate start-up time at all operating modes with minimal design changes.

NOMENCLATURE

GTE - gas turbine engine
APU - auxiliary power unit
NGV - nozzle guide vane
ATS - air turbo starter
IGV - inlet guide vane
K_G - mass flow parameter
K_N - power parameter
P - pressure
T - temperature
G - mass flow rate
α_{IGV} - IGV stagger angle
π - pressure ratio
ΔG - losses (bleeding) of air flow in the aircraft
Δp^* - total pressure losses in the aircraft ducts
ΔT^* - total temperature losses in the aircraft ducts
N - power
p_h - ambient pressure
t_h - ambient temperature
n - rotational speed
M - torque
τ - time

1 INTRODUCTION

The start-up of an aircraft gas turbine engine is an important mode that largely determines the safety, operational efficiency and reliability of the engine and the entire aircraft. The gas turbine engine start-up system includes a set of various devices and units: a starter, auxiliary power unit, air and fuel communications, automatic control system, transmission, power supply system, ignition system, etc. For reliable engine starting, the operation of all these systems must be consistent with each other (Inozemcev et al., 2008).

Currently, the civil aircraft engine starting system is often based on an air turbine mechanically connected to the GTE rotor, receiving compressed air from the APU compressor (Figure 1).

The group of the paper's authors is employed by the Department of Aircraft Engine Theory of Samara National Research University (Samara University, 2020) and has extensive experience in studying and improving the working process of various components of a gas turbine engine (Marchukov et al., 2017; Matveev et al., 2018). Currently, the scientific group takes part in joint work in the interests of various enterprises that are the part of the

[a] https://orcid.org/0000-0003-4491-1845
[b] https://orcid.org/0000-0003-0737-3048
[c] https://orcid.org/0000-0003-2806-3073

Popov, G., Baturin, O., Zubanov, V., Kolmakova, D., Korneeva, A. and Volkov, A.
Optimization of a Single-stage Air Starter Turbine.
DOI: 10.5220/0009769501550162
In *Proceedings of the 10th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2020)*, pages 155-162
ISBN: 978-989-758-444-2

United Engine Corporation (Russia) (United engine corporation, 2020). In particular, one of the Customers set the task of assessing the feasibility of using an air turbostarter manufactured at the enterprise to launch a new turbofan engine of the same class. The design of the considered ATS is shown in Figure 2.

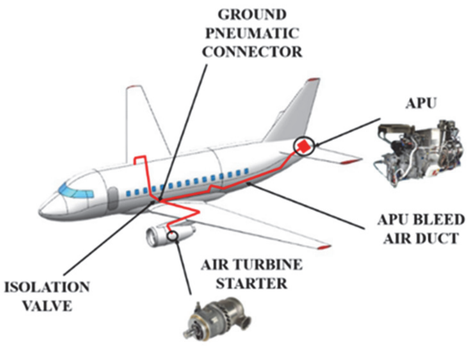


Figure 1: Concept scheme of the starting system with an air turbine.

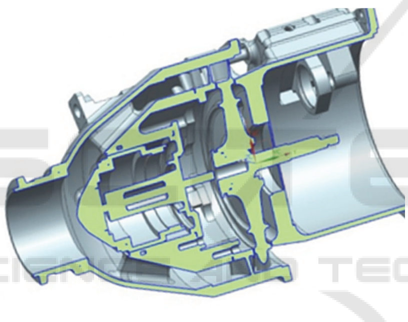


Figure 2: Design of the investigated starter air turbine.

The team was assigned the following tasks:

1) the ATS operation must be coordinated with the operation of the APU at all operating modes (under various atmospheric conditions, flight speeds and altitudes);
2) start-up time must be minimized (the minimum allowed time was set);
3) the torque on the output shaft must not exceed the maximum value according to the strength conditions of the reduction gearbox and gear box of the engine drives.

In other words, the main task was to modify the flow part of the existing ATS so that it would satisfy the above conditions when working in a modified launch system (another gas turbine engine and APU). Moreover, the design of the baseline turbine must be kept as much as possible to reduce costs. Thus, the task is a typical optimization problem in which the turbine geometry must be changed (considering various constraints: structural and strength) to improve the required criterion (start-up time).

In open scientific and technical sources, there are many publications on the modernization and optimization of the turbine workflow (Marchukov et al., 2018; Châtel et al., 2019., Asgarshamsi et al., 2014). However, all of them are aimed at improving the efficiency of turbines or their reliability. In current case, the unusual optimization criteria take place and it is necessary to check the condition for the joint operation of the ATS and APU and to calculate the start-up time of the gas turbine engine during optimization.

To solve the problem, an algorithm was developed for matching the working process of the APU and the air turbine used to start the engine. This method was described in detail in (Zubanov et al., 2019).

The essence of the method is that the characteristics of the APU and ATS are converted to a general form of the dependence of the reduced flow parameter K_G on the expansion ratio of air in the turbine $K_{G\,\mathrm{ATS}} = f(\pi_{\mathrm{ATS}})$. The intersection of the lines of the APU and turbine operating modes suggests that the conditions for joint work are fulfilled at these modes. At the intersection points of the characteristics $K_{G\,\mathrm{ATS}} = f(\pi_{\mathrm{ATS}})$ and $K_{G\,\mathrm{APU}} = f(\pi_{\mathrm{APU}})$, the parameters at the APU outlet $p^*_{\mathrm{APUoutlet}}$, $T^*_{\mathrm{APUoutlet}}$, $G_{\mathrm{APUoutlet}}$ are calculated and with their help the characteristics of the turbine (in particular, the dependence of power on rotational speed) are determined under the found conditions. Then, using the ATS power characteristics, the start time of the gas turbine engine is determined. The algorithm for its calculation is described in (Zubanov et al., 2019). The conformity of the maximum torque to the strength constraints is also checked.

Thus, based on the intersection points of the above characteristics, the physical characteristics of the ATS are found when working together with the APU at all its modes.

The flow parameter K_G is a physical quantity that is calculated using the following expression:

$$K_G = \frac{G_{ATSinput} \cdot \sqrt{T^*_{ATSinput}}}{p^*_{ATSinput}}, \tag{1}$$

where $G_{ATSinput}$ - the value of air mass flow rate through the ATS;

$T^*_{ATSinput}$ - the value of the total temperature at the ATS inlet;

$p^*_{ATSinput}$ - the value of the total pressure at the ATS inlet.

When calculating the flow parameter K_G for the APU, leakages and pressure and temperature losses in the pipelines of the launch system on the way to the turbine are considered.

$$K_{G\ \mathrm{APU}} = \\ = \frac{(G_{\mathrm{APUoutlet}} - \Delta G) \cdot \sqrt{(T^{*}_{\mathrm{APUoutlet}} - \Delta T^{*})}}{p^{*}_{\mathrm{APUoutlet}} - \Delta p^{*}_{hydr.}}, \quad (2)$$

$$\pi_{\mathrm{APU}} = \frac{p^{*}_{\mathrm{APUoutlet}} - \Delta p^{*}_{hydr.}}{p_h}, \quad (3)$$

where $K_{G\ \mathrm{APU}}$ – APU air mass flow parameter determined at the inlet of the ATS considering losses in the pipelines;

π_{APU} – pressure ratio in the ATS determined by the parameters of the air at the inlet to the ATS considering losses in the pipelines;

G_{ATSinput} – the value of the mass flow rate of air taken from the APU considering losses in the pipelines, $\left[\frac{kg}{s}\right]$:

$$G_{\mathrm{ATSinput}} = G_{\mathrm{APUoutlet}} - \Delta G \quad (4)$$

$T^{*}_{\mathrm{ATSinput}}$ – the value of the temperature of air taken from the APU considering losses in the pipelines, (К):

$$T^{*}_{\mathrm{ATSinput}} = T^{*}_{\mathrm{APUoutlet}} - \Delta T^{*}, \quad (5)$$

$p^{*}_{\mathrm{ATSinput}}$ – the value of the total pressure of air taken from the APU considering losses in the pipelines, $\left(\frac{kgf}{cm^2}\right)$:

$$p^{*}_{\mathrm{ATSinput}} = p^{*}_{\mathrm{APUoutlet}} - \Delta p^{*}_{\mathrm{hydr.}}, \quad (6)$$

p_h – atmospheric pressure for altitude in standard atmospheric conditions, $\left[\frac{kgf}{cm^2}\right]$.

Values of losses of mass flow rate, temperature and pressure in the system are set by the Customer according to the experience of operating an engine of a similar class. The dependence $K_{G\ \mathrm{ATS}} = f(\pi_{\mathrm{ATS}})$ obtained for the used APU is shown in Figure 3.

Characteristics of the turbine of the form $K_{G\ \mathrm{ATS}} = f(\pi_{\mathrm{ATS}})$ (Figure 4) were obtained by CFD modelling of the working process in the investigated turbine (Figure 2). Its mathematical model was created using NUMECA software system. The model included a structural grid of finite volumes of 92 thousand elements. The value of the parameter y+ did not exceed 1. The Spalart-Allmaras turbulence model was used. In general, the settings of the numerical model of an air turbine corresponded to the typical settings used in the calculation of the working process in turbines (Popov et al., 2018).

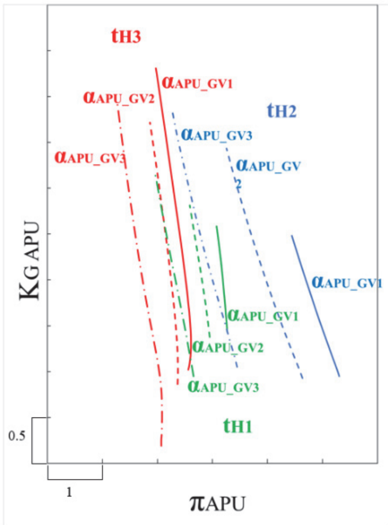


Figure 3: Characteristics $K_{G\ APU} = f(\pi_{APU})$ of used APU.

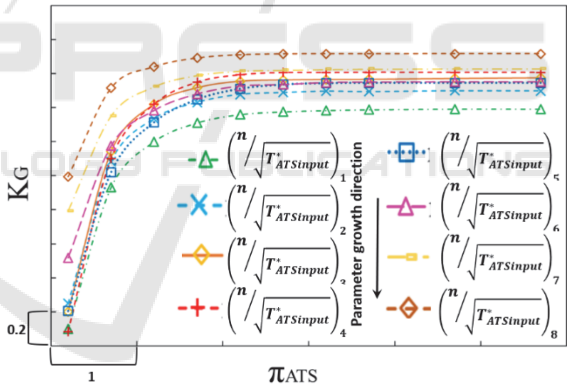
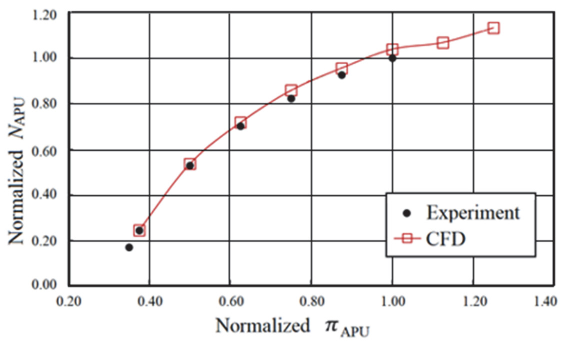


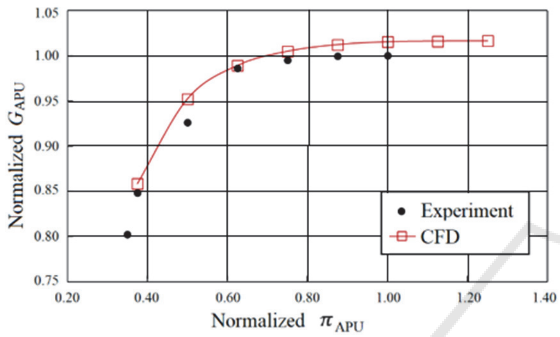
Figure 4: Mass flow characteristics $K_{G\ ATS} = f(\pi_{\mathrm{ATS}})$ of investigated air turbine.

The calculation results obtained using the created calculation model were compared with the experimental data provided by the customer (Figure 5). The relative error in determining the ATS power was less than 2.5%, and the air mass flow rate was less than 2%.

The characteristics $K_G = f(\pi_{ATS})$ for the ATS and APU were combined at one diagram (Figure 6).



Power characteristics



Mass flow characteristics

Figure 5: Comparison of calculation results obtained with the created computational model with experimental data.

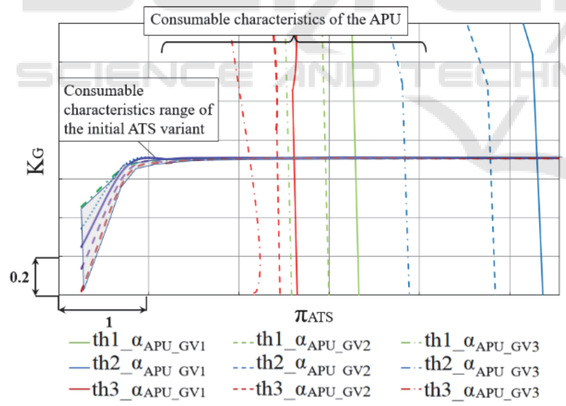


Figure 6: Combined flow characteristic of the APU and ATS.

As can be seen from Figure 6, all the lines of APU and ATS operating modes intersect, which indicates that the condition for their joint operation is fulfilled at all operating modes. However, it was found during the calculation, that the start-up time of the gas turbine when using the ATS exceeds the value specified in the technical requirements by 12.6%. At the same time, the maximum torque on the turbine shaft did not exceed the permissible value. Thus, it is necessary to increase the turbine power (without exceeding its limit value) and the air flow through it in order to reduce the start-up time to use the turbine for a new GTE start system.

Analysis of the turbine working process showed that the required increase in the turbine power and mass flow rate can be achieved with minimal changes in the initial design only by modernizing the shape of the nozzle guide vanes. In the other words, the modernization of the existing ATS to the new requirements can be performed while substantially preserving the design. In fact, only one part will be changed that is the nozzle block.

2 PARAMETRIC STUDIES

To search for a possible solution, parametric studies were conducted on the influence of these parameters on the start-up time.

2.1 Changing the NGV Stagger Angle

During the study of the influence of the stagger angle of NGV on the flow rate of the working fluid and the power of the turbine, the angle varied in the range of +2° relative to the initial value. In total, five points were considered (including the initial geometry) with a step of 0.5°. A larger change in the angle will lead to a change in the design of adjacent parts and a significant amount of alteration of the original design.

The obtained dependences of the mass flow parameter K_G, start-up time and torque on changes in NGV stagger angle are shown in Figure 7. It can be seen that with a maximum increase in the NGV stagger angle, the start-up time of the gas turbine engine was reduced by only 7.6%. This value is 5.7% higher than the limit value (i.e., such a turbine does not satisfy the requirements). The maximum value of torque was 27.5% less than the maximum allowable, which meets the requirements of the technical specifications. Thus, changing only the stagger angle within the existing constraints on the axial length of the NGV part is not enough to increase the turbine power and to reduce the start-up time of the GTE.

2.2 Trimming the Trailing Edge of NGV

Five variants for trimming the trailing edge of the NGV were considered (Figure 8). The dependences of the flow rate parameter K_G, start-up time and torque on the value of trimming the NGV trailing edge are obtained. They are shown in Figure 8. It can be seen from the presented results that, the start-up time was reduced by 10.7% by trimming the NGV trailing edge, which is 2.1% more than the maximum allowable τ_max. The maximum torque value was 21.8% less than the maximum allowable M_{torque_max}.

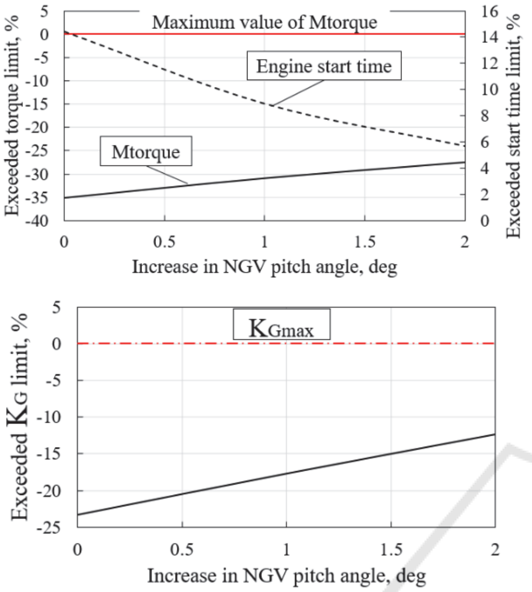


Figure 7: Dependences of the parameters of the starter turbine and the start-up time of the gas turbine engine on the stagger angle of the ATS NGV.

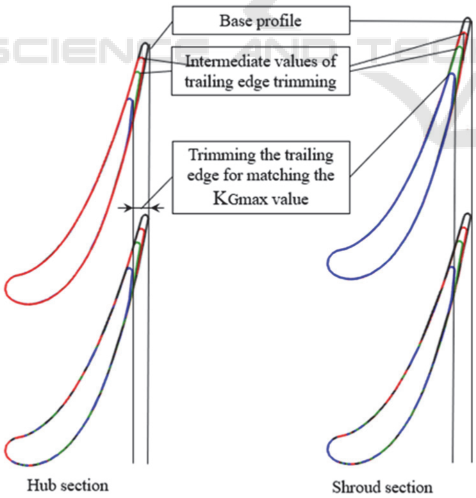


Figure 8: The hub and shroud sections of the NGV variants with trimming trailing edge.

Thus, trimming the NGV trailing edge also does not provide the GTE start-up time specified in the technical task. During the study, it was found that the proposed modernization options cause significant deviations of the inlet flow angles for the rotor blade, which are the reason of significant dynamic stresses in it.

Thus, none of the considered variants of ATS modernization satisfies the requirements of the technical specifications with its design is preserved to the maximum. For this reason, it was decided to use mathematical optimization methods to find an acceptable variant.

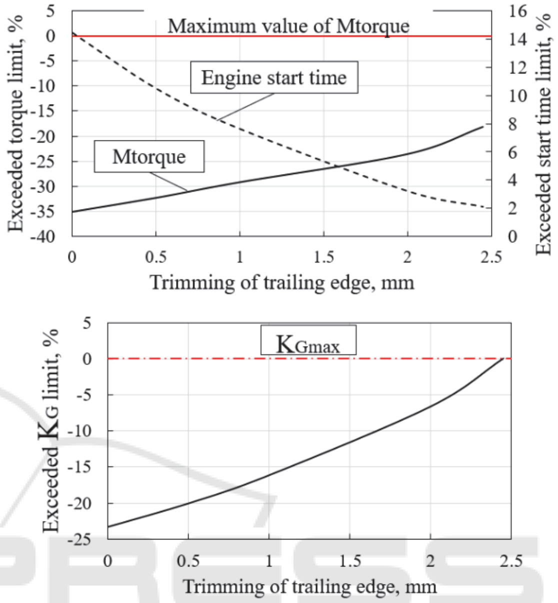


Figure 9: Dependences of the mass flow parameter $\boldsymbol{K_G}$, start-up time and torque on the value of trimming the NGV trailing edge.

3 OPTIMIZATION ALGORITHM FOR STARTER AIR TURBINE

A further search for a new shape of ATS NGV was carried out using multicriteria mathematical optimization methods. For this, an algorithm was developed that is built around the IOSO optimizer program (IOSO, 2020). The choice of the IOSO program is due to the large number of its successful application in the tasks of aircraft engine field, including by the authors of the paper (12-17 Marchukov et al., 2019; Marchukov et al., 2019; Marchukov et al., 2018; Marchukov et al., 2017; Salnikov et al., 2019; Buyukli et al., 2017). The specified program was used as a finished commercial product. No upgrades were made to optimization algorithms. A description of the algorithms used in the program can be found on the website and publications of the program developer.

The schematic diagram of the developed ATS optimization algorithm is shown in Figure 10. At each optimization step, the *IOSO PM* optimizer generates a vector of input parameters x_1, x_2, x_3, …, x_n. The values of the input parameters describe the profile geometry of the nozzle guide vanes in a parametric form. The vector of variable parameters is transferred to the reprofiling unit, in which the *Numeca AutoBlade* program (Numeca AutoBlade, 2020) converts the blades and saves them as geometry files in the *.*GeomTurbo* format. Then, *Numeca AutoBlade 5* creates a mesh model using new blades. At the next step, CFD calculation is performed with the new mesh model. Processing the results of CFD modeling is performed by a special script using *Numeca FineTurbo* (Numeca FineTurbo, 2020) and small applications from the NET Framework library. As a result, several output files are created containing the ATS operation parameters of interest in the text format. Then these parameters are transferred to the IOSO optimizer, where the results are processed and the current optimal variant of the ATS NGV is selected, and a new set of input parameters x_1, x_2, x_3, …, x_n. is created. This process is iterative and runs until the desired extremum is found, taking into account the given constraints.

The goal of optimizing the flow part of the ATS is to reduce the start-up time of a gas turbine engine while reducing the torque on the turbine output shaft (in order to increase the reliability). The presence of two optimization criteria ensures more stable operation of the IOSO optimizer (Kuzmenko et al., 2007).

Based on the foregoing, the following criteria were selected for optimization:

1) GTE start time (it must be reduced);
2) the torque on the turbine shaft (it must be reduced).

The following parameters were set as constraints:

1) the torque at all modes must be less than the maximum allowable value;
2) the flow parameter K_G must be within the range K_{G_min}… K_{G_max}, where the value K_{G_min} corresponds to the minimum value of K_G from all operating modes of the APU, and K_{G_max} - to the maximum value of Kg from all operating modes of the APU. This requirement is necessary to fulfill the conditions for the joint work of the APU and the ATS at all operating modes.

The parametrization scheme for the sections of the ATS nozzle guide vanes is shown in Figure 11. Changing the geometry of the first nozzle guide vanes was carried out in two control sections (hub and shroud). Each section was described by 14 independent variables (chord, inlet and outlet design angles, profile stagger angle, edge radii, position of control points of the spline of the pressure side and suction side, etc.). In total, 28 variables were used to describe the geometry of the ATS nozzle guide vanes.

Such a statement of the optimization problem makes it possible to find the Pareto front of optimal solutions in which each value of the gas turbine engine start-up time corresponds to the minimum torque at which it can be achieved (Figure 12). Then, in accordance with the task requirements, a variant is selected that provides the minimum start-up time, that can be achieved with a torque value acceptable under the conditions of transmission strength. Obviously, the requirement to reduce the start-up time will shift the selected point on the Pareto front to the left as far as possible, as much as the torque limitations allow.

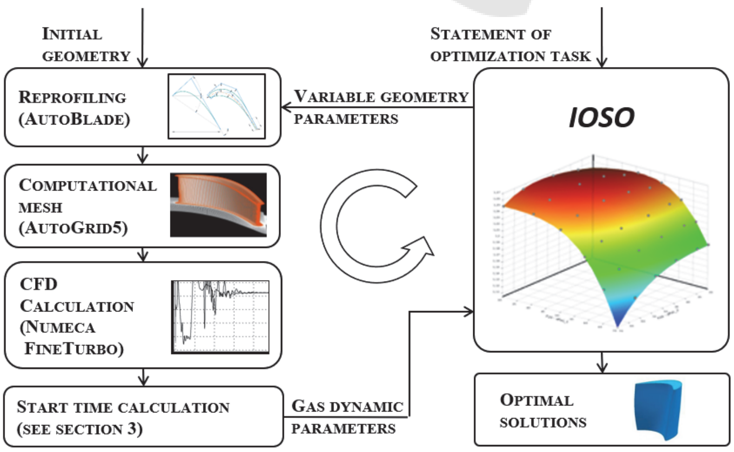


Figure 10: Schematic diagram of the applied methodology for multicriteria optimization of ATS.

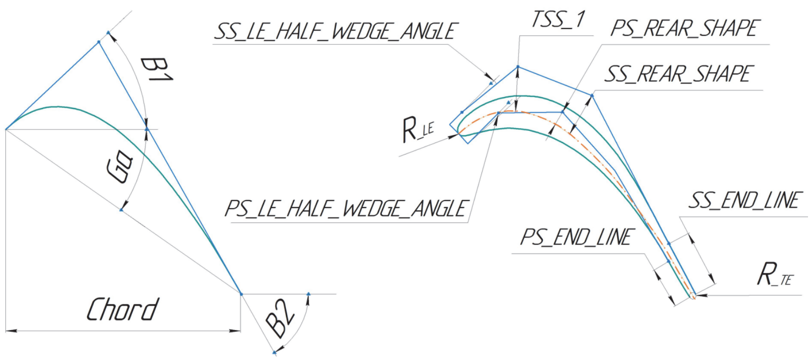


Figure 11: Parametrization scheme for the sections of the ATS nozzle guide vanes.

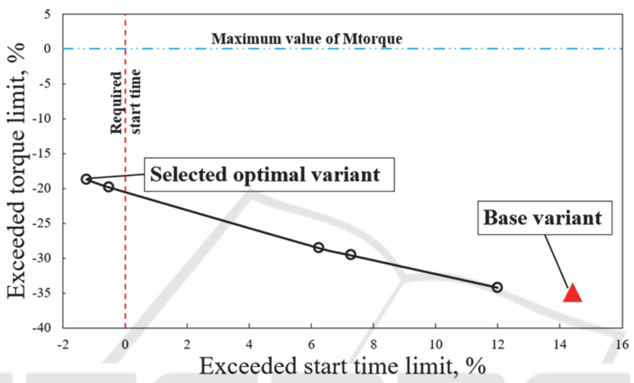


Figure 12: Pareto Front "Torque - Engine Start-Up Time" of the ATS variant at the most loaded operating mode.

4 OPTIMIZATION RESULTS

The optimization process was stopped after 200 calculation cycles. As a result, the Pareto front was obtained between the values of the start-up time of the gas turbine engine and the torque on the output shaft of the ATS (Figure 12).

For the current problem, the case with maximum torque and minimum start-up time is of the greatest practical interest. The start-up time of the gas turbine engine for the selected variant decreased by 13.7% relative to the variant with the baseline ATS geometry and was 1.3% less than the maximum permissible according to the technical requirements. The maximum torque among all the matched operating modes of the APU did not exceed the maximum allowable M_{torque_max} by 18.5%. The value of the mass flow parameter K_G remained within the specified limits $K_{G\_min}...K_{G\_max}$ and was less than the value K_{G_max} by 3.8%. The latter circumstance ensured the preservation of the coordinated work of the APU and ATS at all operating modes. Thus, the main practical goal of the study was achieved.

Figure 13 shows a comparison of the NGV cross-sections of the optimized and baseline ATS variants. The increase in the cross-sectional area and, accordingly, the flow parameter K_G, occurred due to a decrease in the blade thickness, and due to a decrease in the chord of the blade, especially in the shroud section. Since the shape of only the stator blades was adjusted, the strength of the most loaded turbine elements did not change significantly.

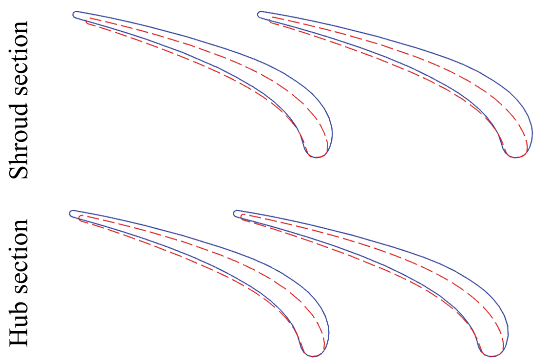


Figure 13: Blade-to-blade sections of ATS NGV: solid line - the baseline variant; dashed line - optimized variant.

5 CONCLUSIONS

This paper presents the results of the modernization of the flow part of an existing air turbine for starting system for application at another engine of the same class. It was shown that the initial turbine satisfies the requirements of working together with the APU at all operating conditions, provides satisfaction of strength requirements, but the start-up time when using it exceeds by 12% the maximum time required in the technical specifications. During the analysis, it was found that it is necessary to increase the power of the turbine by increasing air flow rate in order to fulfil the requirements. Changing the parameters of the turbine was carried out by changing the shape of the NGV. Conducted parametric research did not allow to find a solution. Therefore, the problem was solved using the original algorithm using a commercial optimizer program. As a result, a solution was found that made it possible to find such a configuration of the turbine flow path only by changing one element (NGV unit) that ensures that the technical requirements in terms of starting time are met with a margin of 2%. In this case, the maximum torque on the turbine shaft is 18% less than the permissible value and the conditions for the joint operation of the turbine and the APU are fulfilled at all operating modes.

REFERENCES

Inozemcev, A. A., Nihamkin, M. A. and Sandrackii, V. L. 2008. *Fundamentals of designing aircraft engines and power plants*. Moscow: Mashinostroenie, 2008. – V.2. – 368 p

Samara University, Access mode: https://ssau.ru/english/

Marchukov, E., Egorov, I., Popov, G., Baturin, O., Goriachkin, E., Novikova, Y. and Kolmakova, D. 2017. Improving of the working process of axial compressors of gas turbine engines by using an optimization method, In *IOP Conference Series: Materials Science and Engineering*.

Matveev, V., Baturin, O. and Popov, G. 2018. The Optimization of Four-Stage Low Pressure Turbine with Outlet Guide Vane. In *IOP Conference Series: Materials Science and Engineering*.

United engine corporation, Access mode: https://www.uecrus.com/eng/

Marchukov, E.Yu., Egorov, I.N. 2018. Gas Dynamic Modernization of Axial Uncooled Turbine by Means of CFD and Optimization Software, In *IOP Conference Series: Materials Science and Engineering*.

Châtel, A., Verstraete, T., Coussement, G. 2019. Multipoint optimization of an axial turbine cascade using a hybrid algorithm. In *Proceedings of the ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, Phoenix*, United States.

Asgarshamsi, A., Hajilouy-Benisi, A., Assempour, A., Pourfarzaneh, H. 2014. Multi-point optimization of lean and sweep angles for stator and rotor blades of an axial turbine. In *Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, Dusseldorf*, Germany.

Zubanov, V. M., Matveev, V. N., Popov, G. M., Novikova, Y. D. 2019. Maturation of an aircraft gas turbine engine air turbo start unit on the basis of its joint action with auxiliary power plant. In *VESTNIK RGATU imeni P.A. Solov'eva*.

Popov, G., Matveev, V., Baturin, O., Novikova, J., Kolmakova, D. and Volkov, 2018. A. Selection of Parameters for 3D Finite-volume Mesh for CFD Simulation of Axial Turbines. In *MATEC Web of Conferences*.

IOSO Optimization Technology. Access mode: http://www.iosotech.com

Marchukov, E., Egorov, I., Popov, G., Baturin, O., Goriachkin, E. and Novikova, Y. 2019. Optimization of a three spool axial compressor to increase the efficiency of a gas turbine engine, In *IOP Conference Series: Materials Science and Engineering*.

Marchukov, E., Egorov, I., Kretinin, G., Karonic, B. & Fedechkin, K. 2019. Optimization of geometry blade for modern high pressure compressor, In *IOP Conference Series: Materials Science and Engineering*.

Marchukov, E.Y. and Egorov, I.N. 2018. Gas Dynamic Modernization of Axial Uncooled Turbine by Means of CFD and Optimization Software, In *IOP Conference Series: Materials Science and Engineering*.

Marchukov, E.Y., Egorov, I., Popov, G., Salnikov, A., Goriachkin, E. and Kolmakova, D. 2017. Multidisciplinary optimization of the working process of uncooled axial turbine according to efficiency and strength criteria. In *Proceedings of the ASME Turbo Expo*.

Salnikov, A. and Danilov, M. 2019. Multidisciplinary design optimization of a bladed disc for small-size gas-turbine engines. In *Proceedings of the ASME Turbo Expo 2019*.

Buyukli, T., Salnikov, A. and Fedorchenko, Y. 2017. High-loaded compressor blisk-type impeller multidisciplinary optimization. In *Proceedings of the ASME Turbo Expo 2017*.

Numeca AutoBlade, Access mode: https://www.numeca.com/product/finedesign3d

Numeca FineTurbo, Access mode: https://www.numeca.com/product/fineturbo

Kuzmenko, M.L., Shmotin, Yu.N., Egorov, I.N. and Fedechkin, K.S. 2007. Optimization of the gas turbine engine parts using methods of numerical simulation. In *Proceedings of the ASME Turbo Expo 2007*.