Optimization of the working process of the axial compressor according to the criterion of efficiency

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Abstract. The paper shows search results of the optimal shape of low pressure compressor blades of the industrial gas turbine plant using methods of computational fluid dynamics and multicriteria methods of mathematical optimization. The essence of the methods is that an increase in compressor efficiency should be achieved by increasing the degree of compression up to 2%, and reducing the air flow to 8% relative to basic engine parameters. However, the compressor design elements should be retained as maximally unchanged as possible. During the work, the calculation model of the workflow in the test compressor has been developed and verified in the NUMECA software package, the automated algorithm of the blades shape change has been also developed using a small number of variables, while maintaining its stress-strain state. It allows reducing the number of changeable variables more than twofold. As the result of this study, the option of compressor performance was found, which can increase its efficiency by 1.3% (abs.).

1. Introduction

JSC "Kuznetsov" [1], located in Samara, is one of the prominent participants of the GTU Russian market. This company produces a family of gas turbines for driving gas pumping units and power plants ranging from 4 to 32 MW. An important place in this line is taken by engine NK-36ST with the capacity of 25MW. It is made according to the scheme with a free turbine and has a three-shaft gas generator, developed on the basis of the aircraft turbofan engine (TFE).

To increase the attractiveness of this engine for the customers, JSC "Kuznetsov" in conjunction with Samara National Research University developed a variant of the modernization of NK-36ST. This modernization enhances the total efficiency of 3%, while maintaining the capacity and making maximum use of structural elements of the base engine. The engine efficiency increase is planned to reach due to the growth of the total pressure ratio by 22%, increasing the efficiency of turbomachinery by an average of 2%, as well as overspeeding the gas generator rotors. Higher efficiency of the engine at a fixed power required the reduction of the air flow rate through the engine by 8% [2]. As a result, terms of reference for the improvement of all engine components were formed.

In particular, the paper authors were aimed at finding the ways to modernize the three-stage axial low pressure compressor (LPC) of engine NK-36ST (Figure 1). It was necessary to ensure the growth of the LPC efficiency by 1.5% (absolute value,) with a 4% increase of the pressure ratio, 2% of the rotor speed and a decrease of the working fluid flow rate of 8%. At the same time, diametrical and axial dimensions of the compressor flow had to be left unchanged, while maintaining acceptable safety...
2. The strategy of problem solution
To achieve the goal, it is necessary to find such forms of LPC blades which provide a supply of the required work to the flow while maintaining the optimum from the viewpoint of reducing the level of velocity losses and channel diffusion, as well as the flow coordination between adjacent blade rows in the leakage angles.

In the existing conditions, it was decided to use the optimization IOSO program [3, 4] in conjunction with software package NUMECA, having special modules for high-quality simulation of turbomachinery workflows [5]. Parameterization of the blade profile has been implemented in the Profiler program, which is developed by the Department of Aero Engines Theory [6].

Finding an algorithm of the optimal shape of LPC blades is as follows (Figure 2). The IOSO program generates a block of input data on the basis of which the Profiler program generates a new blade geometry and transmits it to a Numeca as a text file. In the Numeca, the computational model is created based on the received information, and calculation of the flow in it is produced as a result of which the efficiency and other parameters of the compressor are determined. IOSO forms a new combination of input data on the basis of the calculation, as well as previous references to the numerical model, and the process is repeated until the desired extremum is obtained.

3. Description of the computational model
A numerical model of the compressor workflow was developed in the software package Numeca Auto Grid 5 [7] to carry out the optimization. The initial geometric model of the computational domain was based on the design documentation provided by JSC "Kuznetsov" and contained the domains of inlet and outlet domains, an inlet guide vane, rotor wheels, guide vanes (Figure 3). The airfoils geometry was transmitted to Numeca in a text format of .geomTurbo, which had been formed previously in program Profiler.

The LPC computational model takes into account the presence of the radial clearances of the rotor blades, the values of which have been taken by the recommendation of JSC "Kuznetsov". Also, the model takes into account the working fluid bleeding behind the rotor wheel of the first stage in an amount of 2% of the air flow through the compressor.

The created model was divided into a finite elements structural grid with integrated funds of the Numeca program. One BR had an average of 300,000 elements. The value of the minimum skewness for it in a three-dimensional mesh was 32 degrees. The Average Aspect Ratio value was about 2000. To improve the quality of the processes description in the boundary layers in both models for the description of turbulence, the optional Extended Wall Function was used. The ideal gas with the properties of dry air was used as the working fluid. Turbulence was assumed to be isotropic in all directions. Model k-ε (Low Re Yang-Shih) was used to simulate the turbulence.
Figure 2. The algorithm for finding the optimal shape of the LPC blades using software package IOSO.

The values of total pressure $p^* = 101,325$ kPa and total temperature $T^* = 288,15$ K at the LPC inlet were set as boundary conditions. The direction of the flow at the computational domain inlet was defined as axial.

Interface Full Non Matching Mixing Plane, integrated in Numeca, was used for data transfer between the domains of GV and RW. This interface averages flow parameters in the circumferential direction in the upstream domain and passes as a boundary condition in the domain located downstream.

4. Parameterization of the profile shape
A slightly modified approach from [8,9] was used to describe the shape of the camber line. The profile camber line was represented as a spline that passes through the four (rotor wheel) or three (for the guide vanes) checkpoints. The ends points of the spline corresponded to the centers of leading and trailing edges. The remaining points were evenly spaced along the spline. Changing the camber line shape of the rotor blades and the relative position of the cross sections relative to each other was carried out by moving the spline middle control points in the circumferential direction in the global coordinate system, as well as by varying the stagger angle (Figure 4, a). This solution helped to keep the value of the blade chord in control sections, which is important in terms of maintaining the stress-strain state.

The guide vane profile was changed by moving the middle point of the spline in the circumferential direction and moving the point of the trailing edge along both coordinates (Figure 4, b).

The geometry of the modernized compressor blades was built on the basic of the LPC NK-36ST geometry. For this, the forms of camber lines, as the locus of the centers of the circles inscribed in the profile, were found in all of the sections. Then, the thickness distribution along the chord of the initial blade was obtained by measuring the distance from the camber line to the profile surface. This information was used to form a new shape of the blade after the change of the geometry camber line [10].
5. The statement of the optimization problem
The optimization problem was solved in a two-criteria formulation. The following was selected as optimization criteria:
- an increase of LPC efficiency at rotor speed \( n = 102\% \) (relative to rotor speed of the base compressor);
- a decrease of the relative flow rate of air through the compressor.

Geometric parameters of each blade in the three control sections were varied according to the algorithm described above during the optimization process. The changing of each section is described by three variables (Figure 4) except the hub sections of the rotor wheels, the stagger angle of which remained to preserve the size of the blade foot. The total number of independent variables is 61. All linear dimensions were changed relatively the initial shape of the blade in the range of \( \pm 0.1b \), where \( b \) – a profile chord. The stagger angles were in the range of \( \pm 5^\circ \).

The constraints that determine the position of the working point on the LPC characteristic were specified for the optimization problem:
- the minimum value of the air flow rate in the design point is limited by the range of
  \[ 0.91 \sigma_c^* \leq \bar{G} \leq 0.96 \sigma_c^* ; \]
- the relative total pressure ratio was maintained at the design point of the following predetermined range:
  \[ 1.009 < \pi_k^* < 1.046 ; \]
- the flow angle at the LPC outlet was limited by the range of \( \pm 5^\circ \).

The last constraints are due to the desire to preserve the conditions of leakage in the elements of the next compressor stage.

6. Optimization results and discussion
Software package IOSO required 1884 references to a computational model for solving the optimization problem.

As a result, by means of Pareto, a set of the best possible criteria according to two criteria - the relative efficiency and the relative flow rate of the working fluid through the compressor - were obtained (Figure 5).
Three points were selected for the optimization results validation and analysis (Figure 5). The pressure characteristics were calculated for each point at the rotor speed of 102% of the base LPC speed and compared with the initial characteristic of the compressor (Figure 6).

Comparing the characteristics of the different variants, it can be seen that all the variants have approximately the same efficiency at the desired air flow rate through the compressor. Moreover, this value is greater than the efficiency of the base compressor by 1.3% (absolute).

Variant №2 was adopted as a final embodiment of the compressor, because it allows obtaining the desired pressure ratio (variant №3 has less value), has a higher efficiency than variant №1 and the stall margin for this variant does not differ from the original compressor stall margin.

Comparison of the blade shapes of base LPC of NK-36ST with a modified variant is shown in Figure 7.

Comparison of the Mach numbers fields in the blade passages and the flow passage of the original and a modified compressor is shown in Figure 8.

Analysis of the results shows that the decrease in the mass flow rate through the compressor led to a decrease in incident flow velocity on the RW and GV blades. This, together with the specification of leakage flow angles on the blade (the disappearance of the local maximum speed directly on the leading edge shows this (Figure 8)) and the shape correction of the input part have led to a substantial decrease in the acceleration zone on the suction side of the rotor blades at the inlet. The nature of the velocity field change in other blade rows is similar. These factors lead to the fact that all three stages of efficiency increased in average by 0.5% (abs.)
Figure 6. Comparison of relative characteristics of the selected LPC variants with the characteristics of the original compressor.

Figure 7. Comparison of the blade shapes of the original (dotted line) and modified (solid line) compressors in the middle section.

Figure 8. Comparison of the Mach numbers fields averaging in the circumferential direction for the maximum efficiency point at branch n = 102%.

7. Conclusions
To summarize the work done, it can be concluded that the goal is achieved in general. The form of low-pressure compressor blades for GTU has been found by the methods of multicriteria mathematical optimization. This modernization provides the efficiency increase by 1.3% (absolute value) with the pressure ratio increasing by 4%, the speed by 2% and the decrease of the working fluid flow rate by 8% relative to the compressor of the base engine. The compressor parameters were modified only by changing the blade shapes while retaining the remaining structural elements unchanged, including the
number of blades and the shape blade foot. Measures to preserve the stress strain state have been taken in the search for improved forms of blades.

The algorithm for the blade shape changing by the use of a small number of variables has been developed in the process of solving the problem, reducing the number of variables by more than half.

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