Application of 3D Navier-Stokes Equations and Mathematical Optimization Techniques to Improve the Efficiency of Seven-Stage Axial Compressor

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Abstract: The paper presents the results of an optimization of the high-pressure compressor of the engine NK-36ST using the mathematical optimization techniques. The article describes in detail the search algorithm of the optimal form of the compressor blades using the software package Numeca and software package IOSO. The description of the used numerical model is given, its verification was carried out. It is shown that only by correcting the stagger angles of the blade rows the efficiency of the considered compressor can be increased by 1.5% at the current position of the working point on the characteristic of the compressor. Also the search possibility of compromise solution that provides a simultaneous increase in the efficiency of the compressor in two modes is shown.

1 INTRODUCTION

The gas turbine plants (GTP) must always be improved to retain a share in the market and to successfully compete with the newly appearing products. The designers and manufacturers of the engines must constantly work to reduce the costs. They should identify and remedy the defects, find actions to increase durability of details, that will increase the engine resource and time of its life. The cost of fuel makes up a large part of the life cycle cost of the engine and the reduction of consumption can provide the significant economic benefits (Kulagin, 2002).

All engine-enterprises are faced with problem described above. Such as JSC "Kuznetsov". This company is located in Samara (Russia) and it is the manufacturer of the GTP for the drive of the gas compressor units and the electric generating station with the capacity from 4 to 32 MW. Over the past five years the company carries out active work to modernize the engine NK-36ST with the capacity 25 MW. This engine is used to drive the gas compressor units. It is made according to the scheme with the free turbine (FT) and it has the three-shaft gas generator based on the aircraft turbofan engine (turbojet). The company is conducted the search operations that is aimed at the overall efficiency increasing of the engine for 2...3%. Samara State Aerospace University (SSAU) also is involved in this work. The work on the modernization of the engine NK-36ST is supported by Government of Russian Federation.

The series of the thermodynamic calculations was carried out in SSAU and it was shown that the components of the high-pressure stage and the FT have the greatest influence on the working process and efficiency of the GTP. The values of the coefficients of impact on the overall efficiency (Kulagin, 2002) of the high pressure compressor (HPC), the high pressure turbine (HPT) and the FT are equal to 0.167, 0.202 and 0.284 (Kuzmichev, Rybakov, Tkacheno, Krupenich, 2014).

To the authors team of the this article it was tasked to find the ways of the HPC efficiency increase of the engine NK-36ST for the operation mode which is corresponding to 100% capacity of the power plant (25 MW). This compressor is axial, seven stage, subsonic. The value of the pressure ratio at $n=100\%$ is $\pi_к^*=4,2$. In order to reduce the manufacturing costs of the modernized version the JSC "Kuznetsov" has set severe restrictions. It was forbidden to change any elements of the rotor and stator except blades, but also the shape of blade airfoil should remain unchanged as much as possible. In fact, to obtain the compressor efficiency increase it is planned to correct only the stagger

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angle of compressor blades. In addition, the quite tight deadline were set for obtention of the first results.

2 THE USED COMPUTATIONAL MODEL

Comercial CFD software package NUMECA and software of the mathematical optimization IOSO is used for solving the problem.

The initial geometric model of the computational domain was based on the design documentation provided by JSC "Kuznetsov" and it contained domains of the middle bearing, inlet guide vanes, and blade wheel (BW), guide vanes (GV) and output area (Figure 1). The geometry of the blades airfoils transmitted to NUMECA as text files in the format *.geomTurbo*, which previously had been formed in the software Profiler developed in SSAU (Shablii, Dmitrieva, 2014). The geometry of the computational domain took into account the changes in the diameter of the compressor under the influence of the heat and centrifugal loads (Matveev, Popov, Goryachkin, Smirnova, 2014).

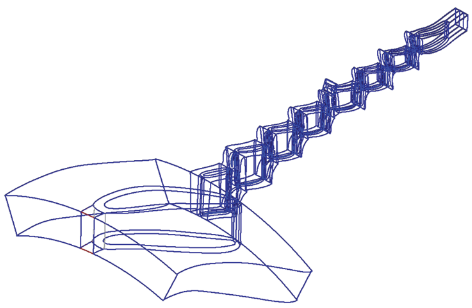

Figure 1: HPC computational model of NK-36ST.

The calculation model of the HPC took into account the presence of a radial clearance over the rotor blades, the values of which in the operation have been taken on the recommendations JSC "Kuznetsov". Also in the model, the presence of the working fluid bleed after the BW of fourth turbine cooling stage in an amount of 2.75% of the total air flow rate at the compressor inlet was taken into account.

The created model was divided into the finite volumes by block-structured grid using internal tools of the software NUMECA. Two grid models were created. Model №1 contained two million of the finite volumes. On average the one BR had 120 thousand of the finite volumes. The maximum value of the parameter y + for this grid was 12. Model №2 contained 8.2 million of the finite volumes. On average, the one BW had 500 thousand of the finite volumes. The maximum value of the parameter y + for this grid was 1. To improve the description quality of the processes in the boundary layers in both models, in the description of turbulence the option *Extended Wall Function* was used.

Comparison of the finite volumes mesh of the models №1 and №2 is shown in Figure 2. In the considered computational domain the space around the rotor blade and guide vanes was allocated.

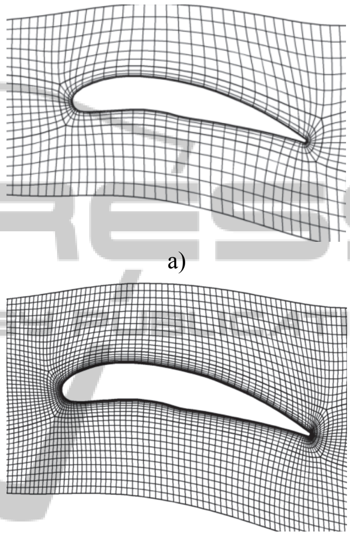

Figure 2: Comparative picture of the finite volumes grid of the models №1 (a) and №2 (b).

As the boundary conditions at the inlet of the HPC the value of the total pressure was set equal to $p^*=101,325kPa$ and the total temperature was equal to $T * = 288,15K$. The flow direction at the inlet of the computational domain $\alpha = 30^0$ is relative to the axis of rotation. k-ε turbulence model was used. Parameters of the turbulence at the inlet boundary are $k=5m^2/c_2$, $\varepsilon=30000\ m^2/c_3$.

To evaluate the quality of the grid models created by program *Numeca Fine Turbo* the characteristics head branches of the engine NK-36ST were calculated at rotor speeds *n=90, 95, 100* и *102%* (the rotational speed *n=100%* corresponds to the GTP work at power in the output shaft is equal to *25 MW*). The obtained results were compared with the experimental studies data of the considered compressor which was provided by JSC "Kuznetsov".

Characteristics are presented as the parameters that correspond to the operating mode with the rotor speed of 100 rev / min.

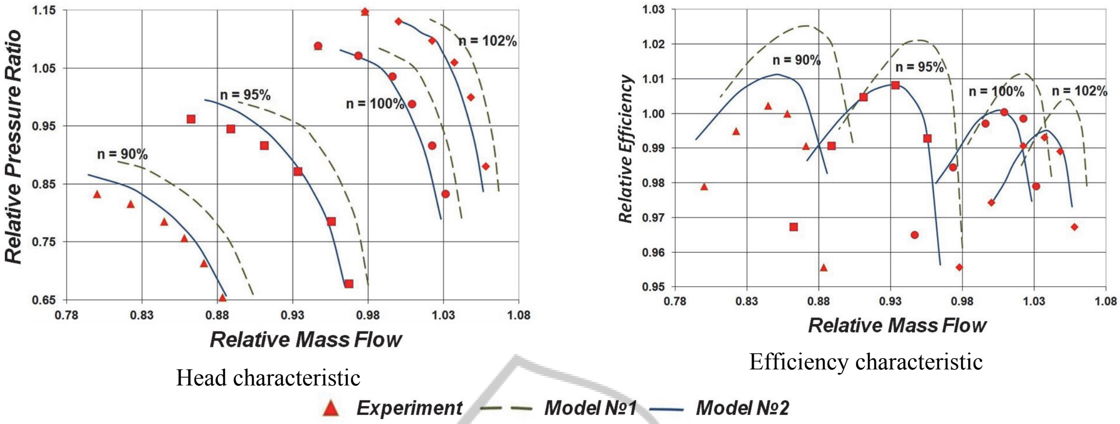

Figure 3: Comparison of the characteristics, obtained by the different grid models, of the investigated HPC with the experimental data.

The results of the comparison are shown in Figure 3. It shows the dimensionless characteristics of the NK-36ST HPC as two dependences: the relative compression ratio and the relative efficiency of the relative air flow rate through the compressor.

As it can be seen from Figure 3, the both created numerical models show the good qualitative coincidence with the experimental results. However, the model №2 shows significantly better quantitative coincidence with the experimental results. The difference of values for the efficiency and the compression ratio is not more than 2%. For this reason, the model №2 was used for further studies. Streamline workflow of the HPC BY THE GUIDE VANES stagger angle of the first stages/

In the first phase, by agreement with JSC "Kuznetsov", it was decided to find out how the HPC efficiency can be improved at operation mode is n = 100% by changing the stagger angles of the guide vanes of the first three stages (Figure 4). The range of variation of the stagger angles was limited by company to ±5° of the initial values for the maximum preservation of the parts of the existing engine.

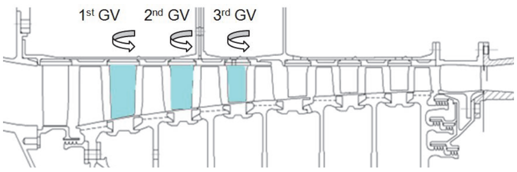

Figure 4: Guide vanes, the stagger angles of which have changed.

It was decided for finding the maximum efficiency to use the methods of the mathematical optimization. In particular, the program IOSO was used. It is based on the optimization method which based on the creating of the response surface, which is refined and evolved for each access to calculation model. A detailed description of the algorithm IOSO can be found in the work (Egorov, Kretinin, Leshchenko, Kuptzov, 2002).

The search algorithm of the optimal geometry of the compressor on the basis the three-dimensional numerical simulation under the control of program optimizer IOSO (Figure 5) was developed to solve this problem. It is as follows. The program *IOSO* generates the input data block based on which the software *Profiler* changes the geometry of the blades (changes the stagger angle) and transmits it as the text file in *NUMECA*.

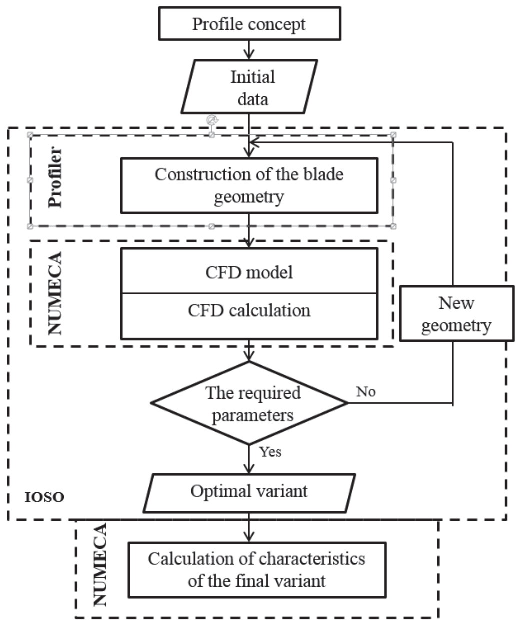

Figure 5: Search algorithm of the optimal form of the compressor blades using the software package IOSO.

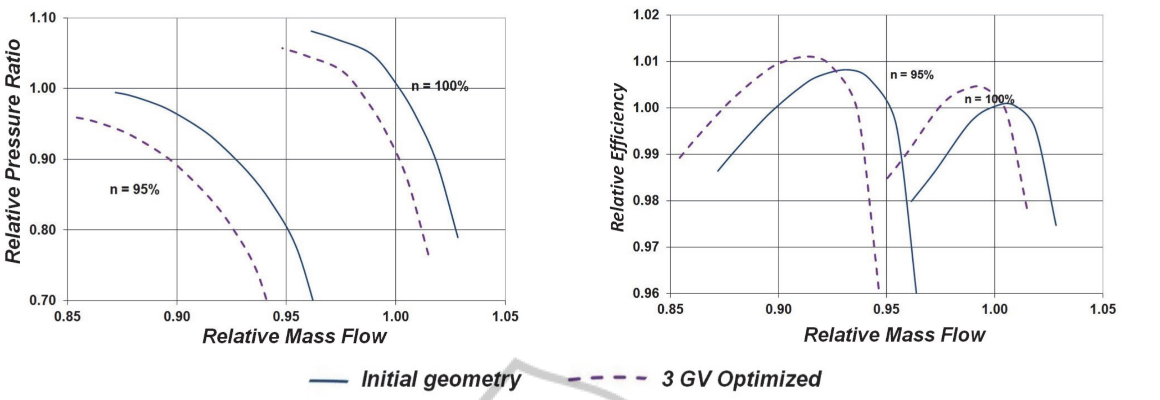

Figure 6: Comparison of the characteristics of the initial HPC with characteristics of the compressor with optimized stagger angles of the first three stages.

There, on the basis of the obtained information, the computational model was created and the flow was calculated in it as a result of which the compressor efficiency and other parameters is determined, the results were written to the output file. IOSO wrote this file and on the basis of calculation, as well as calls to previous numerical model, created the new combination of the input data and the process is repeated to the required extremum.

The software package IOSO had 102 calls to computational model to solve the problem of optimization. The total computation time was more than 150 hours of computer time on cluster of 10 PCs.

Figure 6 shows comparison of the characteristics of the initial and optimized version of the HPC. An analysis of the obtained results shows that by decreasing the stagger angles of the GV in 1, 2 and 3 stages at 1.9480, 1.9470 and 1.7290 degrees respectively it succeeded to increase the efficiency of the compressor at the HPC rotor speed n = 100% to 0,3% (abs.). The efficiency increase caused by matching of the contact angles of the first stages. The decrease in the GV stagger angles has led to the fact that the сщккусеув specific air flow rate in the considered mode is decreased by 1.3%, that may cause the decrease in the engine power.

Thus, it was demonstrated that by correcting of the stagger angles of the GV it's possible to achieve the increase of the HPC efficiency, but this increase is not a significantly. In addition by the results of the study it had concluded to save the joint work of nodes while optimizing it should the impose restrictions on the position of key operating point on the characteristic of the compressor. Streamline workflow HPC by stagger angles of all blade rows.

According to the studies results which described above the JSC "Kuznetsov" was convinced that the significant increase of the efficiency of HPC is not possible by changing the number of the blade rows . For this reason, the task has been adjusted. It was instructed to determine how the efficiency of the considered HPC can be increased by changing of the blade rows stagger angles, which are placed there. Together with this it was tasked to achieve the efficiency increase of the HPC not only at rotational speed of 100%, but at rotational speed of 95%, while maintaining the flow rate and the compression ratio at these operation modes.

To reach the given task the problem of optimization has been changed. Maximum efficiencies of the compressor at the relative rotational speeds of 95% and 100% were selected as optimization criteria.

In order to prevent the shift of characteristics of the compressor, in agreement with the JSC "Kuznetsov", the following restrictions were set in the optimization:

– the flow rate of the working fluid through the HPC at the relative frequency of rotation of 95% was not supposed to be different from the respective flow rate of the base compressor more than ±1,3%;
– the flow rate of the working fluid through the HPC at relative frequency of rotation of 100% was not supposed to be different from the respective flow rate of the base compressor more than ±0,6%;
– the value change of the HPC pressure ratio in comparison with the base compressor at points of the maximum efficiency at relative rotational speeds of 95% and 100% was allowed within ±1,5%.

The stagger angles of all rotor blades, the GV and IGV of the HPC were selected as varied variables.

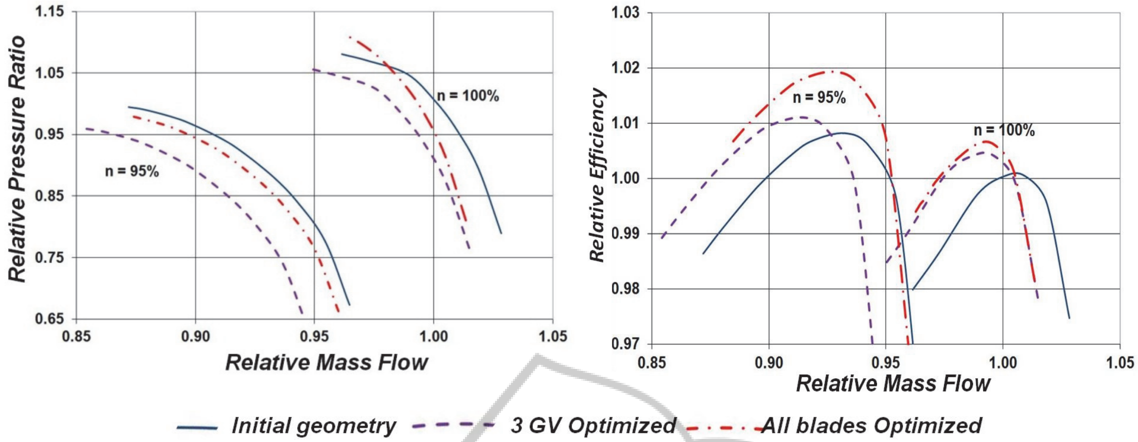

Figure 7: Comparison of the characteristics of optimized versions of the compressor and basic HPC.

The range of the stagger angles change of the vanes of each blade row has been selected so that during the blades rotation their profiles fits into the existing blade stoppers. The blades number in the row wasn't changed. This solution allowed to find the variant to increase the efficiency of the HPC, that would not require the modification of the disk and the body parts of the compressor. The total number of the changed variables was 15.

To solve the formulated problem of the optimization the software package *IOSO* had 446 calls to the numerical model of the HPC. Each call to the numerical model is calculation of two points on the characteristic of the HPC (points of the maximum efficiency on the branches corresponding to the relative frequency of the rotation of 95% and 100%) in the software package *NUMECA FineTurbo.*

As a result, a lot of unimprovable solutions (Pareto set) were obtained, which are a compromise between the increase of efficiency at the relative rotational speed of 95% and the increase of efficiency at the relative rotational speed of 100% (Figure 8). Each point of Pareto set corresponds to the unique geometry of the HPC which is represented as an array of the stagger angles of all blade rows of the HPC.

Analysis of the extreme points of Pareto set shown that at relative rotation frequency of 95% the highest increase of the maximum efficiency is 1.8% (abs.) at the substantially constant maximum efficiency at the relative rotational speed of 100% (point 1 of Pareto set in Figure 8). When the relative rotational speed is 100% the highest increase of maximum efficiency is 0.6% (abs.) at the increase of the maximum efficiency at relative rotational speed of 80% to 1% (point 2 Pareto set in Figure 8). However, for further research the one of midpoints of the set Pareto have been selected (point 3 in Figure 8), which is provide the increase of the efficiency as at relative rotation frequency of 100% (0.5% (abs.)) and at the relative frequency rotation of 95 % (1.2% (abs.)).

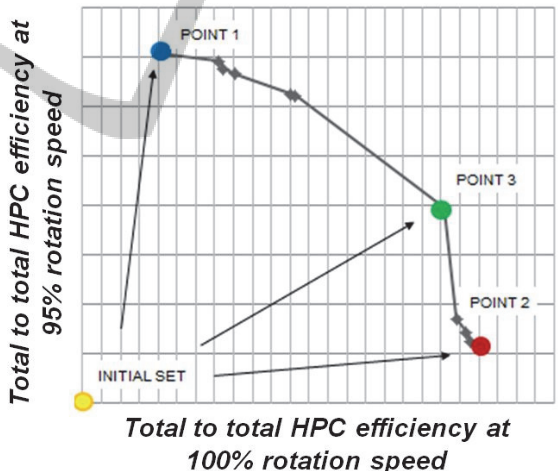

Figure 8: Pareto set.

The numerical model of the HPC corresponding to the selected point #3 of the Pareto set was created to analyze the results of the optimization. The characteristics of optimized version of the HPC at the relative rotational speeds of 95% and 100% were obtained by this numerical model and their comparison with the characteristics of the HPC base version (Figure 7) and with the searching results of the optimal combination of the stagger angles at the first three stages was performed.

As the result of the comparison the following characteristics was revealed:

- the operation stall margin of the optimized HPC was changed slightly in comparison with the base case at the investigated rotation frequencies;
- the values change of the air flow rate and the compressor pressure ratio of the optimized HPC at points of the maximum efficiency at the investigated rotation frequencies is within the accepted limits;
- the HPC efficiency at the relative rotation frequency of 95% has increased by 1.2% (abs.) and at relative rotation frequency of 100% the increase of efficiency was 0.5% (abs.).

Analysis of the flow structure in the optimized version of the HPC at the point of the maximum efficiency at the relative rotation frequency of 100% shown that the optimization of the HPC blades stagger angles has removed the stall in the hub section of the fourth and fifth HPC BW (Figure 9).

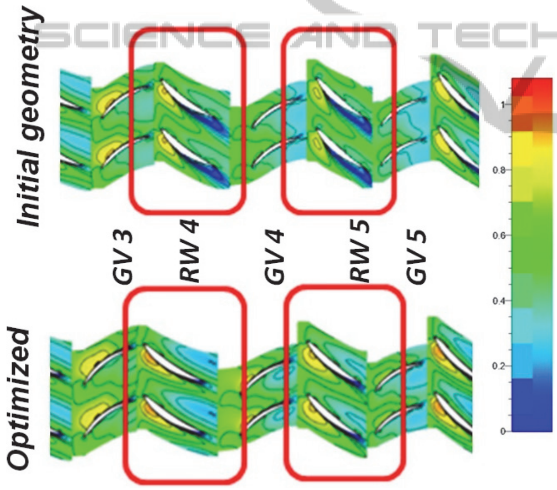

Figure 9: Comparison of the fields of the relative Mach number near the hub section of the base and optimized HPC.

3 CONCLUSIONS

As a result of the work described above the searching algorithm the optimal form of compressor blades by numerical models of workflow in program NUMECA and optimizer program IOSO has been developed and implemented.

The adequacy of the developed method has been proved by the example of solving the problem of optimization of the high pressure compressor of real gas turbine plant.

It was found the configuration of the compressor allowing to obtain improved efficiency by 1.2% at the rotating frequency of 95% and efficiency by 0.5% at the rotation frequency of the rotor of 100%.

Changing the shape of blades,the guide vanes and the flow part during optimization has allowed to obtain the higher values of efficiency of the compressor.

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