Increase of Gas-Turbine Plant Efficiency by Optimizing Operation of Compressors

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Abstract. The article presents optimization method for improving of the working process of axial compressors of gas turbine engines. Developed method allows to perform search for the best geometry of compressor blades automatically by using optimization software IOSO and CFD software NUMECA Fine/Turbo. The calculation of the compressor parameters was performed for work and stall point of its performance map on each optimization step. Study was carried out for seven-stage high-pressure compressor and three-stage low-pressure compressors. As a result of optimization, improvement of efficiency was achieved for all investigated compressors.

1. Introduction
Using CFD during the axial compressor design can reduce cash costs, but the search for the best version of the flow channel geometry takes a lot of time. The main reason is that the flow channel geometry of axial compressor stages is described by large number of variables. At least two sections, each of which is determined by dozens of independent variables, must be determined to describe the shape of one blade. Furthermore, it is necessary to describe the relative position of the sections relative to each other, shape of meridional section of the flow part, etc. As a result, the number of independent variables for a complete description of one stage reaches several tens which affect contradictory compressor characteristics. Man is not capable physiologically to analyse the problem of such dimension. The problem becomes proportionally larger if it is necessary to investigate the operation of multistage compressor.

In this case, the optimization program can help the engineer. Their use allows the automatization of the search for the optimal combination of independent variables by their automatic variation and analysis of the results based on optimization algorithms.

This article shows the technique for improving of the working process of axial compressor using optimization software IOSO and CFD software NUMECA Fine/Turbo and shows examples of the application of this technique on real seven-stage high-pressure compressor and three-stage low-pressure compressors of NK36-ST gas turbine engine (figure 1). The aim of optimization was to investigate which maximum efficiency is possible to obtain in each compressor [1]. The criteria and constraints for the optimization problems of each compressor have been selected on the basis of thermodynamic calculations of the engine NK36-ST [2].
2. **Numerical model of compressors used for optimization**

Numerical LPC and HPC models were created for the study based on the project documentation submitted by JSC "Kuznetsov" [3] in the Numeca software (figure 2).

The created model was divided into finite volumes to block-structured grid by internal tools of the program NUMECA. Two computational models (“light” - Model № 1 and “heavy” - Model № 2) were created for each compressor. Light model contained 300 thousand elements per blade row on an average; the value of $y^+$ was 3-5. Heavy model contained 500 thousand elements per blade row on an average; the value of $y^+$ was 1-2.

As the boundary conditions at the inlet of the HPC and LPC the value of the total pressure was set equal to $p^*=101,325$ kPa and total temperature was equal to $T^* = 288.15K$. Parameters of turbulence at the inlet boundary are $k=5m^2/c^2$, $\varepsilon=30000$ m$^2$/c$^3$. In the calculation of characteristics the stall borderline was defined as the point with the minimum flow rate of the working fluid, in which it managed to get the coincided decision [4].

To prove the validity of the numerical models LPC (figure 3) and HPC (figure 4) characteristics were calculated at several operational modes. Then they were compared with the available experimental data for the compressors.

The calculated parameters of the compressor are presented in relative form:

$$\bar{n}_{cor} = n_{cor}/n_{cor, BASE} \cdot 100\%$$ (1)

where $n_{cor, BASE}$ – the rotor speed at the primary operational mode of the base LPC;

$n_{cor}$ - corrected rotor speed;

$$n_{cor} = n\sqrt{288.15/T_H^*}$$ (2)

where $n$ - specific rotor speed;

$n$ – physical rotor speed;

$T_H^*$ - air temperature at engine inlet.

*Normalized Efficiency* – efficiency referred to efficiency at the primary operational mode of the base LPC.

*Normalized Pressure Ratio* – pressure ratio referred to efficiency at the primary operational mode of the base LPC.
**Normalized Mass Flow** – air flow rate referred to efficiency at the primary operational mode of the base LPC.

As can be seen from figure 3, both created numerical models show good qualitative coincidence with the experimental results. However, the model №2 shows significantly better quantitative coincidence with experimental results. The difference of values for efficiency and the compression ratio is not more than 1%.

Apparently from figure 4, calculated pressure characteristics of the LPC qualitatively repeat the experimental ones. The maximum deviation of calculated values of the pressure ratio from the experimental value is 1% (abs) at the mode $\bar{n}_{\text{cor}} = 84\%$. Also, figure 4 shows that calculated curves of efficiency characteristic of the base LPC qualitatively repeat the experimental ones at all modes. The maximum difference between calculated and measured efficiency is 2.9% (abs.) at the mode $\bar{n}_{\text{cor}} = 84\%$. At the mode $\bar{n}_{\text{cor}} = 100\%$, the maximum deviation is 0.7% (abs.).

Based on the above, it was concluded that, despite some quantitative discrepancies with the available experimental data, created numerical model can adequately describe the operation of the LPC and can be used for search of configuration with maximum efficiency. For this reason, the model №2 was used for further studies.

3. **Optimization of HPC of the engine NK36-ST**

The criteria for this optimization problem:
- increase in HPC efficiency at the mode corresponding to the rotational speed of 95%;
- increase in HPC efficiency at the mode corresponding to the rotational speed of 100%.

In order to prevent the shift of characteristics of the compressor, in agreement with JSC "Kuznetsov" [4], the following restrictions were set in the optimization:

Flow rate of the working fluid through the HPC at relative frequency of rotation of 95% was not supposed to be different from the respective flow rate of the base compressor more than $\pm 1.3\%$;

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 $\pm 0.6\%$;
value change of HPC pressure ratio compared with the basic compressor at points of the maximum efficiency at relative rotational speeds of 95% and 100% allowed within ±1.5%.

As varied variables the stagger angles of all rotor blades, guide vanes and IGV of the HPC were selected. The range of change of stagger angles of the vanes of each blade row has been selected so that during the blades rotation their profiles fits into existing blade locks. The number of blades in the row has not changed. This solution allows to find the variant to increase the efficiency of the HPC, which would not require modification of the disk and the body parts of the compressor. The total number of changed variables was 15.

The whole optimization process was completely automated.

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

Analysis of the extreme points of Pareto set shown that at relative rotation frequency of 95% the highest increase of maximum efficiency is 1.8% (abs.) at a substantially constant maximum efficiency at relative rotational speed of 100% (point 1 of Pareto). When the relative rotational speed of 100% the highest increase of maximum efficiency is 0.6% (abs.) at the increasing of maximum efficiency at relative rotational speed of 80% to 1% (point 2 Pareto).

However, for further research one of midpoints of the set Pareto has been selected (point 3 of Pareto), providing increasing of the efficiency as at relative rotation frequency of 100% (0.5% (abs.)) and at the relative frequency rotation of 95 % (1.2% (abs.)).

To analyse the results of the optimization the numerical model of HPC variant was created, which corresponds to the selected point 3 of the Pareto set. By this numerical model the characteristics of optimized version of HPC at the relative rotational speeds of 95% and 100% were obtained as well as their comparison with the characteristics of HPC base version (figure 5) and with the searching results of the optimal combination of stagger angles at the first three stages, described above, performed.

The result of comparison revealed the following characteristics:
- stall margin of operation of optimized HPC compared to the base case at the investigated frequencies of rotation have changed slightly;
- changing the values of the air flow rate and compressor pressure ratio of the optimized HPC at points of maximum efficiency at the investigated frequencies of rotation is within the accepted limits;
- HPC efficiency at the relative rotation frequency of 95% has increased by 1.2% (abs.) and at relative rotation frequency of 100% increase of efficiency was 0.5% (abs.).

4. Optimization of LPC of the engine NK36-ST
On conditions of the problem, it was necessary to ensure the growth of the LPC efficiency by 1.5% (absolute value) with 4% increase of pressure ratio, 2% of the rotor speed and decrease of the working fluid flow rate by 8% with respect to the parameters of the original engine NK-36ST. The goal is to be achieved with unchanged diametrical and axial dimensions of the compressor flow, while maintaining acceptable safety margins of all the rotor elements.

![Graph](image-url)
Figure 5. Comparison of the characteristics of optimized versions of the compressor and basic HPC.

Optimization problem was solved in a two-criteria formulation. As optimization criteria were selected:
- increase of LPC efficiency at rotor speed n = 102% (relative to rotor speed of the base compressor);
- decrease of the relative flow rate of air through the compressor.

The constraints that determine the position of the working point on the LPC characteristic specified for the optimization problem:
- minimum value of the air flow rate in the design point is limited by the range: 0.91 ... 0.96·base;
- the total pressure ratio was maintained at the design point a predetermined range: 1.009 ... 1.046·base;
- the flow angle changing at the LPC outlet was limited by the range: ±5 degrees.

Varying variables were selected as follow. Slightly modified approach from [5] was used to describe the shape of the camber line. 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 by varying the stagger angle. 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.

Reforming algorithm of the blade profile along the height with the approaches described above has been implemented in the «in-house» program, developed at the Department of Aircraft Engines Theory of SSAU. This program allows to convert a table of coordinates, which describes the blade shape in design drawing into text files of source data.

To solve the formulated problem of optimization the software package IOSO had 446 calls to the numerical model of the HPC [6]. Each call to the numerical model is calculation of two points on the characteristic of the HPC (points of maximum efficiency on the branches corresponding to the relative frequency of rotation of 95% and 100%) in the software package NUMECA FineTurbo. As a result, the Pareto set of best possible criteria according to two criteria - the relative efficiency and the relative flow rate of the working fluid through the compressor were obtained. Three points were selected for the optimization results validation and analysis.

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 efficiency of the base compressor by 1.3% (absolute). Comparison of relative characteristics of the selected LPC variants with characteristic of original compressor Variant №2 was adopted as a final embodiment of the compressor, because it allows to obtain the desired pressure ratio (variant №3 has less value), has a higher efficiency than the variant №1 and stall margin for this variant does not differ from the original compressor stall margin.

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5. Conclusion
Summing up the work done it can be concluded that the goal has been reached. The developed algorithm showed its effectiveness for the reprofiling multistage turbomachinery.

HPC variant has been found that provides an increase in the efficiency at the operation mode corresponding to 95% of the rotational speed by 1.2% (absolute) and at the mode corresponding to 100% of the rotational speed by 0.5% (absolute).
Also a variant of the shape of low pressure compressor blades has been found that provides an increase in efficiency by 1.3% (abs.), while increasing the pressure ratio by 4%, the rotational speed by 2% and decrease in the mass flow rate of working fluid flow by 8% relative to compressor of base engine.

During the search for improved shapes of blades, measures for the conservation of their stress strain state in the former borders were taken. It would be difficult to obtain a similar result with traditional methods of designing compressor as the base variants of the compressor already had a high level of efficiency, and the requirements were contradictory.

Figure 6. Comparison of characteristics of the selected LPC variants with characteristic of original compressor.

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