Increasing the efficiency of the axial low pressure compressor in three operation modes by optimizing the shape of its blades

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Abstract. The paper proposes a method for multicriteria optimization of the low pressure compressor working process. The optimization was conducted in three engine modes, corresponding to the temperature of the air at engine inlet -15, +15, +45 °C. Parameters of the compressor were calculated in operational and stall points. The LPC modernization was performed with usage of optimization methods that implemented in the software package IOSO. To perform optimization, the LPC numerical model was created using the NUMECA FineTurbo software. Numerical models of the LPC workflow were created based on the design documentation. The coordinates of three points of a spline in a circumferential direction and a stagger angle were changed for the rotor blades. The coordinates of a mid-point and a point of the trailing edge, stagger angles, and also the position of sections in circumferential and axial directions were changed for the guide vanes. To prevent a shift of the LPC characteristics, we set restrictions for the LPC specific massflow, a minimal pressure raise and stall margin. As a result of this work, a variant of the compressor, ensuring the increase in its efficiency by 1.1% (abs.) and stall margins by 7.5% (abs.) in the primary operation mode has been found.

1. Introduction
After an aircraft engine has fulfilled its resource, it has become possible to apply it for driving gas-compressor units, generators, etc. This approach makes it possible to meet the needs of the energy market in terms of lack of time and material resources for design and construction of gas turbine units (GTU) "from scratch" [1]. In particular, that approach has been applied at Samara enterprise JSC "Kuznetsov" for creating GTU NK36-ST with a capacity of 25 MW. The base engine was a bypass turbojet aircraft engine with afterburner. That engine was developed in the 1980s.

It was decided to upgrade the engine to increase its efficiency up to 39% and to increase power on a free turbine shaft up to 32 MW.

Thermodynamic calculations that have been carried out by scientists of Samara State Aerospace University showed the fundamental possibility of improving the engine efficiency. It is possible to increase the efficiency up to 39% with an increase in power up to 32 MW due to the modernization of engine units. At the same time, a prerequisite was to keep the parts which are the most expensive in manufacturing. They are shafts and wheels of compressors and turbines.

It was decided to design a new LPC for the parameters obtained in the thermodynamic calculations while upgrading the engine forced up to 32 MW.

This paper describes the gas-dynamic refining of a newly designed LPC of the GTU using
mathematical optimization.

2. Description of the numerical model

The computational model of compressor operation was created in the Numeca Auto Grid 5 software package [2]. An initial geometric model of the computational domain was based on the design documentation of LPC. The model contained domains of inlet and outlet areas, the inlet guide vane, rotor wheels and guide vanes (Figure 1).

![Figure 1. The finite volume mesh of the compressor numerical model.](image)

The computational model of the LPC takes into account the presence of radial clearances over the rotor blades [7]. The model also takes into account the bleeding of the working fluid behind the rotor wheel of 2% of the air flow through the compressor [4].

The numerical model was created in the stationary axisymmetric statement. It took into account the deformations of the blades under the influence of acting forces. It was assumed that the hub section remains unchanged, and the tip section is rotated by some angle. The angle of section turning was calculated linearly in other sections. The angle was found during the strength calculation by a beam model [1].

Turbulence model \( k-\varepsilon \) (Low Re Yang-Shih) was used in the calculations [6].

The created model was divided into finite volumes of a structural mesh using Numeca Autogrid 5. The model contained 2.3 million elements (on average 300 thousand elements per one blade row). The value of the minimum skewness for the model was 26 degrees in the three-dimensional grid. An average value of Aspect Ratio was 2000.

The values of total pressure \( p^* = 101.325 \text{ kPa} \) and total temperature \( T^* = 288.15 \text{ K} \) were set as boundary conditions at the LPC inlet. The flow direction in the inlet region was set as axial. The values of static pressure was set at the outlet.

Calculated characteristics were compared with experimental data for the base variant of the LPC. Fig. 3 shows a comparison between calculated characteristics of the base LPC of the GTU and experimental data. Parameters are presented in the following relative form:

\[
\pi_{cor} = \frac{n_{cor}}{n_{corBASE}} \times 100\% ,
\]

where \( n_{corBASE} \) – the rotor speed in the primary operational mode of the base LPC;

\( n_{cor} \) - corrected rotor speed,

\[
n_{cor} = n \sqrt{\frac{288.15}{T^*_H}} ,
\]

where \( n \) - physical rotor speed;

\( T^*_H \) - air temperature at the engine inlet.

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

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

Figure 2 indicates that calculated characteristics of upgraded LPC are both qualitatively and quantitatively consistent with the characteristics of upgraded LPC.

The maximum deviation of calculated values of the pressure ratio is 2.4% (abs.) in the given mode. In this case, the deviation does not exceed 0.5% (abs.) in the operating modes.

Based on the above-mentioned, it was concluded that, despite some quantitative discrepancies with the available experimental data, the created numerical model can adequately describe the operation of the LPC and can be used for search of the configuration with maximum efficiency.

Figure 2. Comparison of calculated characteristics of the base LPC of the GTU with experimental data.

3. The algorithm for solution of the optimization problem

The searching algorithm of the optimal LPC configuration using the optimization methods is shown schematically in Figure 3. In brief, the essence of the algorithm is as follows. A set of input parameters that control the geometry of LPC blades is formed by IOSO [8]. The compressor geometry is reconstructed in the Profiler program based on them. The computational domain corresponding to the reconstructed geometry of the compressor, is built in NUMECA AutoGrid. Then, the numerical calculation of the LPC parameters is performed in the solver of NUMECA FINE/Turbo in several modes of the LPC operation. Calculated parameters of the LPC are returned to IOSO, where selection of compressor variants is produced. Further, a Pareto front and a new set of input parameters are formed. Then, the cycle is repeated until the desired result will be obtained.

The coordinates of three points of a spline in the circumferential direction and the stagger angle were changed for the rotor blades. The coordinates of a mid-point and a point of the trailing edge, stagger angles, and also the position of sections in circumferential and axial directions were changed for the guide vanes (Figure 4).

Figure 3. The algorithm of the LPC optimization.

4. Statement of the optimization problem
The optimization criteria were:
- an efficiency increase in mode $\pi_{cor} = 100\%$ in the point corresponding to the operational mode;
- an increase of the stall margins in mode $\pi_{cor} = 100\%$.

The inlet air temperature varies widely depending on the climatic conditions during engine operation.

Therefore, additional restrictions were imposed for modes $\pi_{cor} = 92\%$ and $\pi_{cor} = 111\%$. Mode $\pi_{cor} = 100\%$ corresponds to the engine mode when the outdoor temperature is $t_h = +15^\circ C$. Mode $\pi_{cor} = 92\%$ corresponds to the engine mode when the outdoor temperature is $t_h = +45^\circ C$. Mode $\pi_{cor} = 111\%$ corresponds to the engine mode when the outdoor temperature is $t_h = -15^\circ C$.

Thus, the goal was to improve the efficiency and the stall margins in the primary operational mode and to avoid the LPC parameters degradation in mode $\pi_{cor} = 92\%$. The mass flow parameter should be maintained in mode $\pi_{cor} = 111\%$. There were no restrictions on the operational parameters in this mode.

Restrictions on the parameters of the LPC are shown in Table 1 (formulation 1) and Table 2 (formulation 2).

The problem was solved in two formulations differing in the range of variable parameters in mode $\pi_{cor} = 92\%$. This is because it was necessary to preserve the position of the operating point on the compressor operating line in primary mode $\pi_{cor} = 100\%$. At the same time, a wide range of parameters’ change was in mode $\pi_{cor} = 92\%$. Formulation 2 was implemented in order to establish whether the restrictions in secondary modes $\pi_{cor} = 92\%$ and $\pi_{cor} = 111\%$ are the limiting factors of the efficiency growth in primary mode $\pi_{cor} = 100\%$.

Symbols in the tables are: MF – Mass Flow, PR – Pressure Ratio, Eff – Efficiency, $\alpha_{out}$ - a flow angle at the LPC outlet; WP – Working Point, SP – Stall Point, CP – Choking Point. SM – Stall Margin.

Table 1. Limitation of the LPC parameters in formulation 1

| $\pi_{cor}$ | MF  | PR  | Eff   | $\alpha_{out}$ | SM   |
|-------------|-----|-----|-------|----------------|------|
| 92%, WP     | ±1 %| >0,99 Base | >0,99 Base |                |      |
| 92%, SP     | <0,99 Base | >0,99 Base | >0,99 Base |                |      |
| 100%, WP    | ±1 %| >Base  | >Base  | ±3 %           | >Base |
| 100%, SP    | <0,99 Base | >Base  | >Base  |                |      |
| 111%, CP    | ±1,0 %         |       |       |                |      |

Table 2. Limitation of the LPC parameters in formulation 2

| $\pi_{cor}$ | MF  | PR  | Eff   | $\alpha_{out}$ | SM   |
|-------------|-----|-----|-------|----------------|------|
| 92%, WP     | ±3 %| >0,97 Base | >0,97 Base |                |      |
| 92%, SP     | <0,97 Base | >0,97 Base | >0,97 Base |                |      |
| 100%, WP    | ±1 %| >Base  | >Base  | ±3 %           | >Base |
| 100%, SP    | <0,99 Base | >Base  | >Base  |                |      |
| 111%, CP    | ±2,0 %         |       |       |                |      |

5. Solving of the optimization problem. Analysis of the results

The result of the optimization problem is a Pareto set of compromise solutions between the efficiency increase and the stall margins' increase (Figure 5). To analyze the results of optimization, the compressor configuration of formulations 1 and 2, which showed the highest increase in efficiency,
was selected. Pressure and efficiency characteristics were calculated for these variants (Figure 6).

![Figure 5](image)

**Figure 5.** A Pareto front of unimprovable compromise solutions of the LCP in formulations 1 and 2 between the increase of stall margins and the efficiency increase.

![Figure 6](image)

**Figure 6.** Comparison of pressure and efficiency characteristics of the base and optimized variants of the LPC.

The difference between characteristics of the optimized variant and the base variant of the compressor determines the difference in the joint operation of engine components and engine parameters.

A thermodynamic model of the gas turbine power plant was used to analyze the effect of the compressor optimization on power plant efficiency change. The thermodynamic model was created in CAE-systems named ASTRA [3].

Comparison of the blade geometry of the basic LPC and the LPC optimized in formulation 2 is shown in Figure 12.

![Figure 12](image)

**Figure 12.** Comparison of the basic LPC geometry and the geometry of the LPC optimized in Formulation 2.
As shown in Figure 6, pressure and efficiency characteristics of the LPC have changed during the optimization. The comparison of the working lines of the base and upgraded LPC shows that when optimized LPC operates as a part of the engine, the operating point is displaced vertically up. That is, the flow rate of the working fluid will remain the same. Optimized LPC provides a greater pressure ratio than the base one at the points of pressure characteristics with the same value of the air flow rate. An increase in the pressure ratio was 2.7% (abs.) for the air flow rate corresponding to the primary operational mode. The maximum efficiency increase was 1.1% (abs.) subjected to the same air flow rate.

From the comparison of characteristics of the LPC optimized in Formulations 1 and 2, it can be seen that the increase in efficiency in Formulation 2 is higher than in Formulation 1 in mode $\pi_{\text{cor}} = 100\%$. At the same time, there is a decrease in efficiency in Formulation 2 in mode $\pi_{\text{cor}} = 92\%$. Also, the air flow rate was increased by 0.7% (abs.) in Formulation 1, and by 1.7% (abs.) - in Formulation 2 in optimized variants of the mode

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