The Optimization of Four-Stage Low Pressure Turbine with Outlet Guide Vane

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Abstract. The goal of the research was to improve efficiency of four-stage low-pressure turbine with outlet guide vane (LPT) at the design point by optimization the shape of all turbine stator vanes and the stagger angles of all rotor blades. The LPT mathematical model was created by using NUMECA FineTurbo software. Several constraints were imposed the mass flow rate through the LPT and the total pressure ratio at the design point may vary within ±0.5% from the original. Parameters of the stator blade shape and rotor blades stagger angles were obtained. This new geometry of the LPT blades produce a 0.8% increase in efficiency at the design point.

1. Introduction

The improvement of turbine efficiency is always an urgent task of the gas turbine industry [1]. Over recent years, the process of designing and development of efficient turbines made a big qualitative leap associated with the development of computational fluid dynamics (CFD) methods. They can reliably predict the characteristics of the turbine with the features of three-dimensional geometry and to evaluate the impact of geometrical or operational variation on the turbine characteristics.

Despite its apparent simplicity, using CFD methods is difficult [2]. The main reason is that the geometry of axial turbine stage is described by many variables. For a complete description of one stage, the number of independent variables reaches several dozen contradictory affecting the turbine characteristics.

Human is not capable to analyze the problem of such dimension. Also, the search time for optimal combination of variables would be prohibitively large. The problem becomes greater for the multistage turbine. In this case, the methods of mathematical optimization can help the engineer. Their application allows to automate the search of optimal combination of independent variables.

The search algorithm is the following. The optimizer, according to the algorithm for finding the extremum, generates a set of magnitudes of varying variables. Then, computational workflow model is formed in a special subroutine or CFD program. Then, the calculation of the flow in the generated variant is carried out in the CFD program. Its results are transmitted to the optimizer, which forms a new combination of independent variables. Described cycle is repeated until the desired extremum.

2. Subject of research and its numerical model.

With this algorithm, 4.5-stage (4 full stages and straightening blade row installed for the latter) shrouded axial turbine model designed and teste in NASA (Figure 1) was optimized [3].
Based on the original geometry of the turbine, a set of computational models was created. When creating computational models, the following assumptions were made (Figure 2).

1. The flow in each blade row (BR) and turbine cavities have the cyclic symmetry property. Therefore, all models contained only one blade passage with periodic boundary conditions on the sides.
2. The calculation was carried out in a stationary statement.
3. Deformation of turbine blades under the gas load was not considered in the calculation.
4. An ideal gas with properties of the kerosene combustion products was used as working fluid.
5. Specific heat and viscosity of the working fluid depend on its temperature.
6. Turbulence was considered as isotropic in all directions. Spalart-Allmaras model was used.
7. Heat transfer between the walls and the flow was not considered due to the process rapidness.

NGV was calculated in the stationary coordinate system. RW was calculated in the rotating coordinate system, the speed of which coincides with the rotor speed.

Radial distribution of total pressure $p^*$, total temperature $T^*$, flow angle $\alpha$ and turbulent viscosity were used as the boundary conditions at the turbine inlet (Figure 2). These parameters were taken as in turbine tests [3, 4]. The static pressure on the hub radius was set at the turbine outlet. The pressure on the rest radii was calculated automatically by the software according to radial-equilibrium equation. The value of the static pressure at the outlet of the turbine is appointed in accordance with the desired degree of expansion. To transfer data between NGV and RW, *Full Non Matching Mixing Plane* was used.

Three computational models with varying mesh density were created for each considered configuration of the turbine. The basic parameters of the mesh models are shown in Table 1.

**Figure 1.** The appearance of investigated turbine [3].

**Figure 2.** Computational model of 4.5-stage turbine with accepted boundary conditions.
Table 1. Basic parameters of created finite element models.

| number of elements in the 2D layer | number of layers along radial direction | total number of elements | y+ value |
|-----------------------------------|----------------------------------------|--------------------------|----------|
| 4.5St_Mesh 1                      | 7755                                   | 3400000                  | 7        |
| 4.5St_Mesh 2                      | 14835                                  | 8100000                  | 3        |
| 4.5St_Mesh 3                      | 22015                                  | 16040000                 | 1        |

3. Verification of the LPT numerical model.
Using created numerical models, the turbine characteristics (Figure 4) as efficiency and mass flow parameter dependences of the total pressure ratio in the turbine at a constant rotor speed were calculated [5,6]. Hereinafter, the following is meant by mass flow parameter:

\[ A = \frac{G \sqrt{T}}{\rho} \]  

(1)

Figure 3. Comparison of calculated and experimental characteristics of the turbine.

It is clear from Figure 3 that the results obtained by medium and fine mesh slightly differ both qualitatively and quantitatively. This suggests that the mesh size ceases to affect the results when the number of finite element per one blade row of more than 900 thousand. Thus, the grid convergence is achieved. Further mesh refinement will not affect calculation results.

The Figure 3 shows that turbine efficiency is overestimated by 2...3% (abs.) and the mass flow parameter by 2...3% (rel.). However, all created numerical models are qualitatively in a good agreement with test results. This is illustrated by the graph in Figure 5. It shows the relative mass flow parameter and relative efficiency dependences of the total pressure ratio in the turbine. The relative parameters are the ratio of the current value of the variable to its maximum value in considered range:

\[ \bar{A} = \frac{A_i}{A_{\text{max}}} \]  

(2)

\[ \bar{\eta} = \frac{\eta_i}{\eta_{\text{max}}} \]  

(3)

All four graphs in Figure 4 coincide with each other. This suggests that computational models evaluate with high accuracy the change of turbine parameters with the pressure ratio variation. For example, if the calculation shows the change in efficiency of 2% with some change in pressure ratio, in fact it is likely that the efficiency change will be the same even though calculation value of the
efficiency is overestimated. This shows good quantitative agreement of calculation and experimental data.

Two numerical models were selected for optimization of turbine: 4.5St_Mesh1 provides a quick calculation of turbine operating parameters; 4.5St_Mesh2 provides grid convergence – increase in the number of elements does not lead to a significant change in the calculated parameters of the turbine.

![Figure 4](image.png)

**Figure 4.** Comparison of relative calculated and experimental characteristics of the turbine.

4. **Statement of the LPT optimization problem.**

The algorithm for finding the optimal solution was built based on optimizer IOSO [7] and software NUMECA. The geometry of computational is constructed domain based on the array of independent variables generated by the optimizer using program «Profiler» [8].

The algorithm described in [9] was used for turbine optimization. Its main idea is that the thickness of the blade in the control section, and the nature of change along the chord remain unchanged during optimization. This approach can significantly reduce the number of variables, and keep the stress-strain state of the blades in the first approximation. This is because the ratio of the cross-sectional area of the hub and peripheral sections of the blade does not change in a large degree.

The shape of the camber line of the blade in the control section is not the only factor determining the turbine efficiency. Mutual position of sections, form of the leading edge, the shape of the meridian section of flow passage and other factors can affect it. These factors have been deliberately excluded from consideration, as they lead to the critical increase in the number of variables. Optimization process with more than 100 independent variables is not allowed with available license for the program IOSO.

Slightly modified approach from [7] was used to describe the shape of the camber line as a spline passing through 4 points. The end points corresponded to the centers of leading and trailing edges. The remaining points are evenly spaced along the spline. Changing the camber line of the rotor blades and relative position of the sections relative to each other was carried out by moving the spline middle points in the circumferential direction in the global coordinate system, as well by varying stagger angle $\gamma$.

NGV shapes were changed moving the first 3 points of the spline in the tangential direction. Also, shifts of the section in the axial and circumferential directions and the stagger angle of profile $\gamma$ were varied. In total, the shape of the three sections (hub, mean, and shroud) was varied in this way in NGV.

Changing RW blade shape was performed only by the stagger angle for entire blade in a range of $\pm3^0$ to save the stress-strain state of the rotor blade, as well as to reduce the number of variables.

Search for the optimal configuration of the 4.5-stage turbine was carried out by the following algorithm. The IOSO program generates block of input data based on which the Profiler program generates new blade geometry and transmits it to a Numeca as a text file. In the Numeca, computational model is created based on the received information, and calculation is produced. As a result, the efficiency and other parameters of the compressor are determined. IOSO forms a new
combination of input data based on the calculation, as well as previous references to the numerical model, and the process is repeated until the desired extremum.

During optimization, the task of increasing the maximum turbine efficiency at the design mode was set. During the optimization process, the geometric parameters of RW and NG blades described above were varied. The total number of independent variables was 96.

The constraints associated with the peculiarities of the turbine functioning as part of GTE were set: mass flow of the working fluid through the turbine and the gas expansion ratio must not differ from the original values by more than 0.5%.

5. Results of the LPT optimization.
The optimization problem was solved using two numerical models 4.5St_Mesh1 and 4.5St_Mesh2 with an equivalent statement. Configurations of blades which provide maximum turbine efficiency under the above restrictions were found using these models. To obtain a solution, more than 1,000 references to computational model were required by program IOSO.

The results of solving optimization problem using 4.5St_Mesh1 and 4.5St_Mesh2 are qualitatively similar. Characteristics of optimal turbine variants were calculated using model 4.5St_Mesh 2. The results were compared with the characteristics of the original version (Figure 5). Comparison of the original and the optimized blade shape obtained using 4.5St_Mesh 2 are shown in Figure 6.

![Figure 5. Comparison of characteristics of 4.5-stage turbine before and after optimization.](image1)

![Figure 6. Comparison of the blade shapes of 4.5-stage turbine before and after optimization.](image2)

The found turbine configurations of provides the increase in efficiency by 0.8% at design mode (Figure 5). Figure 7 shows a comparison of the efficiency and work of turbine stages for initial and optimized variants at design mode. The optimization resulted in some redistribution of work between the stages: the first two stages were unloaded; the last stages were additionally loaded. Moreover, the specific work of the third stage was increased by 3%. Increase in the efficiency of caused the increase
in the specific turbine work by 0.8% (rel.). The increase in stage efficiency is following: in the first stage - by 0.1%; in the second - by 1.5%; in the third - by 1.2%; in the fourth – by 0.5%.

The shape of the nozzle vanes was largely changed in optimization (Figure 6). They gained a complex spatial form. The shape of rotor blades was changed slightly. The main reason for the efficiency improvement was a decrease in secondary losses in NGV, as well as a matching in leakage angles.

6. Conclusions
Configuration of 4.5-stage axial turbine was found allowing the increase of its efficiency by 0.8% at the design mode. Increase of efficiency was achieved by a radical change in the shape of the nozzle guide vanes, which was carried out by using optimization methods and numerical simulation. The main reason for reduction in losses and increase in efficiency is the secondary losses decrease and negotiating the leakage angles of the flow in different blade rows.

To achieve this goal the computational model was developed and verified by comparing the calculated and experimental data for different number of stages. Also, the investigation of mesh convergence was conducted. It was shown that although the model provides overestimate efficiency of about 2.5%, it allows the obtaining of high-quality results which do not differ from the experimental and is suitable for finding the optimal solution.

Found reserve for the efficiency increasing of the turbine is not a limit. Because of limitations in the available license of optimizer IOSO, attention was focused only on NGV. There were not enough variables to describe the shape of the rotor blades. Perhaps, the change in shape of the rotor blades under the similar algorithm will improve the efficiency of the stages even more. In addition, the change in shape of the rotor blade will require verification of its stress-strain state at each step, which considerably complicates the algorithm for solving the problem. However, verification of strength state in the optimal configuration is a clear direction of the research development [10].

![Figure 7. Comparison of the specific works and efficiency of the initial and optimized turbines.](image)

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References
[1] Kulagin V V 2002 Teoria, raschet i proektirovanie aviacionnyh dvigateley i energeticheskih ustanovok. (Theory, calculation and design of aircraft engines and power plants) (Mashinostroenie, Moskow, Russia) p 616
[2] Lomax H, Pulliam Th H and Zingg D W 2001 Fundamentals of Computational Fluid Dynamics (Springer, Berlin, Germany) p 265
[3] Webster P F 1976 Design of a 4 ½ stage turbine with a stage loading factor of 4.66 and high specific work output NASA CR-2659

[4] Whitney W J, Behning F P, Moffitt T P and Hotz G M 1977 Cold-air investigation of 4 ½ stage turbine with a stage loading factor of 4.66 and high specific work output. I – Overall Performance NASA TM X-3498

[5] Lewis R I 1996 Turbomachinery performance analysis (Elsevier Science&Technology Books Pub) p 328

[6] Belousov A N, Musatkin N F, Rad’ko V M and Kuz’michev B V 2006 Proektmy termogazodinamicheskiy raschet osnovnyh parametrov aviacionnyh lopatochnyh machin (The design of the thermodynamic calculation of the main parameters aviation impeller machines) (Samarskii gosudarstvennyi aerokosmicheskii universitet, Samara, Russia) p 316

[7] Kuzmenko M L, Egorov I N, Shmotin Yu N, Chupin P V and Fedechkin K S 2006 Proc. Of the 6th ASMO UK/ISSMO conference on Engineering Design Optimization, Oxford, UK

[8] Shabliy L S and Dmitrieva I B 2014 ARPN J. of Engineering and Applied Sciences 9 (10) 1849-53

[9] Goryahkin E, Popov G, Baturin O and Kolmakova D 2015 Proc. of the ASME Turbo Expo GT2015-43384

[10] Ermakov A I, Urlapkin A V and Fedorchenko D G 2014 The features of resonance stress scatter in turbine wheels with a weak connectivity of blade vibrations Research J. of Applied Sciences 9(11) pp 795-9