Optimization of geometry blade for modern high pressure compressor

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Abstract.
An integration of CFD-3D codes and modern efficient methods of optimization is essential for the contemporary compressors improvement. In order to solve optimization tasks the insular information exchange circle was created. The data circulates between the mathematical model of the stream in a compressor, the algorithm of compressor’s geometry construction based on parameterization and algorithm of optimization itself. The mathematical model of the compressor covers procedures of mesh generation and calculations using CFD code. This model has been verified by experimental data.

A high-pressure compressor of multi regime gas turbine engine for supersonic civil aircraft has been considered as the object of our study. The goal of the research was to increase the efficiency in the design point with the ensured preset gas dynamic parameters under other modes. The variables for optimization task were installation angles and the shape of the middle line of the profile in three sections along the height of the compressor rotor and stator blades. The total amount of independent variables was 72. As a result of the study the optimal geometry for the stator and rotor blades in supersonic aircraft engine has been obtained. The initial project efficiency had been improved by 1-2%, while stability margin remained constant.

1. Introduction
The aerodynamics of compressor flow is crucial when one tries to improve the parameters of the gas turbine engine. Nowadays, it is impossible to achieve a quality boost of gas-dynamic parameters without numerical methods for calculating the spatial flow CFD 3D. Since the computer technology is constantly improving, it is possible to make extensive use of complex and relatively accurate 3D models (e.g. Computational Fluid Dynamics (CFD) analysis or Finite Element Method (FEM)) for the process optimization tasks, the above methods based. Traditionally, such tasks are formulated as some sort of initial design improvement. In the case a (serial or experimental) engine or its part already exists and can be used as this prototype and their main parameters are known and typical the optimization task is to improve some of these parameters, without worsening others. It is simple and clear for a researcher because he or she can use the verified mathematical model of the real object. However, in real life there is a wide range of research tasks where it is necessary to create completely new products with no existing prototypes. Therefore, before setting and solving the task of optimization extra activity is required to design the basic compressor. In this article, an example of consistent process chain
required to design a high-pressure compressor for a new aircraft type with the use of numerical optimization tasks is presented.

2. The object of study

Supersonic commercial flight has always been a great interest of aircraft design engineers, scientists, and business professionals due to the potential to reduce inter-continental travel time [1, 2]. Nowadays, the improving parameters of turbofan engines have revived the dream of faster-than-sound passenger jets [3]. The analysis of supersonic business jets shows that they have a limited number of passengers -8-10 and the max. velocity of the flight is 2.0.M. The max. flight distance is about 7000 km is explained by the requirement of a non-stop flight from any European city to the eastern coast of the USA and other megacities in South-East Asia, China and Japan. As a rule turbofan engines with or without mixing are considered as power units for the above. There is always a set of conflicting requirements for such an aircraft engine. For example, an increase of cruising speed requires lowering bypass ratio and increasing pressure ratio of the fan. But the requirement to reduce the noise level at the take-off mode results in the necessity to increase the bypass ratio. Such dilemmas may affect any main thermodynamic parameters of the gas turbine engine. Moreover, it is essential to take into account the properties of modern materials while a thermodynamic engine profile is being developed, as well as the specifics of its interaction with the aircraft. One of the plausible engines for a business jet with speed of 2.0 M has following parameters on the take-off mode:

Fan pressure ratio: $\pi_{LPC}^{*} = 3.1$.

High pressure compressor pressure ratio: $\pi_{HPC}^{*} = 6.4$.

Bypass ratio: $BPR = 1.5$.

Let us have a look at some aspects of compressor designing for such an engine.

The most important stages of flight of a supersonic jet are take-off and supersonic cruising. Consequently, the same modes are crucial for an engine. On these modes, high-pressure compressor’s corrected rotor speed ranges from 95 to 100 %. Because of that, it is necessary to obtain as high as possible values of compressor efficiency inside this range. Moreover, it is required that the mass flow on the corrected speed of 95% was not less than given one. It is important because on this mode the airflow will determine engine thrust since the rotor speed and gas temperature in the turbine are limited. Main points under consideration are shown schematically in figure 1.

3. Compressor computational model

Traditionally, the compressor initial design point is a take-off mode, which as a rule corresponds to the engine take-off mode while the fulfillment of requirements for other modes is achieved by the smart distribution of pressure ratio between stages and the control of some compressor stages. The compressor must fulfill some set of required parameters in the design point. These parameters are:
corrected air flow ($G$), pressure ratio ($\pi^{*}$), rotor speed ($n=100\%$), adiabatic efficiency ($\eta^{*}$), stability margin ($\Delta Ks$), etc.

First, the flow path is designed considering the overall dimensions limitations, the amount of stages is defined, the distribution of pressure ratio between stages is calculated, etc. The compressor air-flow path and the blades geometry are generated with the use of flow gas-dynamic calculation and blades profiling. [4] Usually, the process of initial designing is an iteration process when data from previous compressor projects is used. Thus the initial compressor project is obtained. Its performance map can be calculated with the use of 3D CFD methods. Based on these results, the researcher conducts confirmative redesigning of gas-dynamic project and blades geometry in order to reach desired parameters. This iteration procedure under which various compressor variants are generated and analyzed is called “manual optimization” (fig. 2).
Fig. 1 Main points under consideration on the compressor map

Fig. 2 The scheme of “manual optimization”.
The important element of this technological cycle is a 3D-CFD model of a compressor. The generation of such model requires a number of key technological stages which are crucial for correct calculations quality. The first stage is the creation of a correct geometric model. On the one hand, this model should be a simplified reflection of a real object. On the other hand, it should take into account the real condition of rotor blades, tip clearances, etc. The second stage of modeling is the definition of the mesh parameters and the calculation domain. The grid model must accurately discrete regions with complex flow structure. The third stage of modeling is configuring of CFD code. At this stage, the researcher should define the numerical model, both its internal parameters and appropriate turbulence model.

As a result of these steps, 3D-CFD compressor model is obtained, which allows to calculate its performance maps within a wide range of speeds. In figure 3, there is a comparison of calculated and experimental performance maps for a compressor with commensurable pressure ratio. The results obtained suggest a good qualitative assessment of pressure lines in the entire range of rotational frequencies and a satisfactory quantitative assessment of the main gas-dynamic parameters.

In our opinion, an integration of CFD-3D codes and modern efficient methods of optimization is essential for improving contemporary compressors [5-7]. In order to solve optimization tasks, the insular information exchange circle was created. Hereinafter this cycle is called “automatic optimization”. The simplified scheme of this circle is shown in figure 4. As an initial project for “automatic optimization” the project obtained during “manual optimization” was used.

As an optimization tool, IOSO NM algorithm was used [8]. During the process of the algorithm's work, the response surface for the criterion and for the constraints is constructed at each iteration. This response surface is used to find the variables vector, which is then calculated in CFD-3D code. Between iterations, self-organization and evolutionary simulation principles are employed to correct the structure and the parameters of the response surface. IOSO is capable of approximate and optimize objective functions with complex topology (including the ones with local optima) using minimal number of points in the experiment plan. In addition, the advantage of IOSO for this particular task is its robustness to appearance of non-computable domains in the objective function.

The information stored during the search is used to improve the surrogate model. However, both adjusted model and response functions are correct not for the entire initial search area but only for a certain neighborhood of the obtained optimal solution. This ensures purposeful improvement of...
approximating properties only in the area of the optimal solution. Such a procedure noticeably reduces the computation effort of solving complex optimization problems.

Fig. 4 The scheme of “automatic optimization”

4. The results of compressor optimization.

After primary gas-dynamic designing and profiling of blades, the initial compressor project was obtained. The 3D-CFD calculation of the performance map showed that efficiency of this design is not satisfactory in terms of efficiency and gas dynamic stability. Further detailed analysis revealed some “obvious” ways to improve the compressor parameters. It is necessary to emphasize, that the qualification, experience and intuition of a researcher is crucial for the efficiency of such procedures. During “manual optimization” 7 different versions of the geometry was analyzed. As a result of this analysis, the aerodynamic project of 6-stage compressor with following parameters: blade end speed $U_k = 346$ m/c; pressure ratio $\pi^* = 6.4$; adiabatic efficiency $\eta^* = 0.855$; stability margin $\Delta K_y = 30\%$ was obtained. The next step was to assess the possibility of further improving the compressor aerodynamics using automatic optimization.

The design optimization task is formulated as follows:

**Criterion:**
Maximizing of the efficiency ($\eta^*$) at the design point at 100% speed.

**Constraints:**
100% speed:
0.99 \cdot G_{\text{take-off}} \leq G_{\text{opt}} < 1.01 \cdot G_{\text{take-off}}; \\
0.99 \cdot \pi_{\text{take-off}}^* \leq \pi_{\text{opt}}^* < 1.01 \cdot \pi_{\text{take-off}}^*; \\
G_{\text{stall}} > 0.9 \cdot G_{\text{take-off}}; \\
\Delta K_s \geq \Delta K_{s \text{ init}}, \text{ where stability margin is defined as: } \Delta K_s = \left( \frac{\pi^*/G_{\text{stall}}}{(\pi^*/G_{\text{take-off}})^2} - 1 \right) \cdot 100\%; \\
95\% \text{ speed: } \\
0.99 \cdot G_{95\%} \leq G_{\text{opt}}; \\
0.95 \cdot \pi_{95\%}^* \leq \pi_{\text{opt}}^* < 1.05 \cdot \pi_{95\%}^*; \\
\eta_{90\% \text{ preset}}^* \leq \eta_{\text{opt}}^*.

Variables:
Installation angles and shape of the middle line of the profile in three sections (0, 50%, 100%) along the height of the rotor and stator blades except exit stator blade. The shape of the middle line of the profile of the first two transonic impellers is described by 3 variables. The shape of the middle line of all other blades is described by 2 variables.
Total amount of variables - 72: rotor blades row 1 and 2 (2-rotor*3-section *3=18) + rotor blades row 4-6 (4-rotor*3-section*2=24) + stator blades row 1-5 (5-stator*3-section*2=30)

Computational model:
Numeca Fine/Turbo 3D-CFD compressor model [9] calculates 2 points on the compressor map (design point and stability margin) at 100% speed, and one point at 95% speed.

During an automatic optimization process, more than 750 versions had been computed. Optimization criterion improvement history is shown in fig. 6. The design with the best geometry (call №750) was chosen and the compressor map for this design was calculated. The comparison of maps for “initial design”, “manual design” and “optimal design” is shown in fig.7. The obtained version has a higher efficiency in the entire operating speed range of 90-100%. Stability margin at speeds of 100% and 95% did not deteriorate, and by 90% decreased slightly.
The overall scheme of compressor designing is shown in fig.5. The labor costs and the achieved parameters in the design point for each work stage are presented in table 1

![Fig.5 The succession of compressor designing work stages](image)

| Table 1. The labor costs and the achieved parameters for considered design stages |
|---------------------------------------------------------------|
| Labor type          | Time     | Number of versions | \(\eta^*\) (design point) | \(\Delta K_{\text{y}}\) (design point) |
|---------------------|----------|--------------------|--------------------------|-------------------------------------|
| Initial design      | 0.5 month| 1                  | 0.84                     | 15%                                 |
| «Manual» optimization| 2.5 month| 7                  | 0.855                    | 30%                                 |
| «Automatic» optimization | 2 month | 750                | 0.865                    | 32%                                 |
5. Conclusion
The optimal compressor design for a supersonic aircraft has been obtained. This design has the maximum possible efficiency under the assumptions made in the calculation model. The approach was to integrate the optimization algorithm IOSO and 3D-CFD numerical model into one information exchange circle in order to improve the aerodynamic efficiency of the high-pressure compressor. As a result of conducted research, the initial project efficiency has been improved by 1-2%, while stability margin remained constant. The most important parts of the compressor optimization process is the capacity to generate high-quality mesh in the automated mode, 3D-CFD numerical model (verified by experiment) and the efficient optimization algorithm.
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