

# Method for Improving Multi-stage Compressor Parameters using the IOSO Optimizer

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**Keywords:** Parametric Model, Optimization, Efficiency, CFD Simulation, Numerical Model Settings, Multistage Compressor, Profiling.

**Abstract:** In the presented work, an algorithm was developed for finding the optimal configuration of the blades of multi-stage axial compressors using 3D CFD modeling as the main tool and using commercial optimization programs. When developing the algorithm, special attention was paid to the development of a method for parameterizing the shape of the blade and a program based on it, which allow you to automatically change the shape of the blade of the axial compressor. They were used by the authors during optimization as a tool that converts variable parameters into the “new” blade geometry. The created algorithm can be used to improve the basic parameters of the compressor (efficiency, pressure ratio, mass flow rate, etc.) due to the correction of the shape of the blade profiles and their position relative to each other. In this case, the algorithm considers the possible presence of various constraints.

## NOMENCLATURE

GTE - gas turbine engine  
MAC - multistage axial compressor  
FV - finite volume  
RB - rotor blade  
RW - rotor wheel  
GV - guide vane  
 $\pi_c^*$  - pressure ratio  
 $\eta_c^*$  - compressor efficiency  
 $\Delta K_s$  - stability margins  
n - rotational speed  
G - mass flow rate of the working fluid  
 $\alpha$  - flow angle in absolute motion

compressor by 1.0% can increase the specific fuel consumption of a gas turbine engine by up to 0.5% (Kulagin, 2002).

The compressor efficiency is laid at the design stage. Therefore, increasing the efficiency of the design process and the design tools can significantly help to achieve high compressor efficiency.


Recently, compressor design methods have evolved significantly due to the numerical simulations based on the Navier-Stokes equations and the exponential growth of computer capabilities. These factors made it possible to conduct not only a detailed 3D simulation of the working processes of multistage axial compressors, but also to optimize the spatial shape of the blades using mathematical optimization methods.


The latter circumstance allows to create the design variants of the compressor in an automated mode that best satisfy all the design requirements, considering the existing constraints of various kinds. At the same time, the blade that best suits the task can have complex spatial shape (offsets of the sections in axial and circumferential directions, the complex law of changing the chords along the blade height etc.).

There may be an opinion that optimization is a magic tool that allows the engineer to get the best

## 1 INTRODUCTION

One of the most important tasks in gas turbine engine building is to increase the energy efficiency of the engines (to reduce fuel consumption). It is determined by many multidirectional influencing parameters characterizing all components and the entire engine. One of the most significant is the compressor efficiency. The shortfall in the efficiency of each

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compressor variant for each case, with minimal user involvement, which reduces the requirement for the qualification of the designer and the likelihood of errors. However, the use of mathematical optimization in the design and development of the MACs has not yet become widespread. Today, only a small number of successful applications of this method are known, and most of them relate only to individual blade rows and stages.

Among the main difficulties hindering the widespread use of optimization are the following. Firstly, for successful optimization, a 3D numerical model of the MAC workflow is required, which can adequately predict the effect of changes in the design parameters of the compressor on its workflow. Secondly, the mathematical model of the compressor must have an acceptable calculation time, since often at least 1000-3000 iterations with the computational model are necessary for solving the optimization problem. Thirdly, stable parametric models of compressor blades are required coupled with the geometry of the computational domain, which can automatically rebuild the 3D model of the blades. To describe the three-dimensional shape of a compressor blade in a parametric form, many variables are required, and their maximum available number is limited when solving the optimization problem. All the components of the optimization system must be combined within a single automated software that works stably in the entire possible variation range of the parameters with minimal user involvement.

The contradictory nature of the requirements and the absence of stable working parameterization tools are the main reasons why multicriteria optimization techniques are currently used to a limited extent when modernizing multistage compressors.

In the presented work, the authors set as the goal the development and practical testing of methods and tools for multicriteria optimization of the MAC flowpath elements using numerical parametric three-dimensional models of their working process. Hereinafter, the MAC efficiency criteria are understood as: efficiency  $\eta_c^*$ , pressure ratio  $\pi_c^*$  and gas-dynamic stability margin  $\Delta K_s$ .

## 2 REVIEW OF THE OPTIMIZATION METHODS AND TOOLS FOR THE COMPRESSOR

At the first stage, an analysis of the MAC optimization experience was carried out based on the

available scientific and technical publications. Summary of the information showed that the usage of optimization methods is one of the most promising ways for improving the design methods and gas-dynamic modernization of the MAC.

In the works (Safari et al., 2013; Ning et al., 2016; Yan et al., 2017), there are examples of optimizing compressor stages using genetic optimization algorithms (genetic algorithm). A genetic algorithm is a search algorithm used for the optimization and simulation problems by randomly selecting, combining, and varying the desired parameters using mechanisms like natural selection.

In papers (Yang et al., 2016; Zamboni et al., 2016; Vasilopoulos et al., 2017), the adjoint methods are used to find the optimal shape of the axial compressor blades. With this approach, the objective function, as well as the gradient function are calculated after the creating the vector of independent variables. Then, the necessary changes in the vector of independent variables are calculated based on the gradient function, and the cycle is repeated until the desired result is achieved. An important advantage of this method is that the rate of convergence of the optimization problem is practically independent of the number of variable parameters.

In (Barsi et al., 2014), the examples of optimizing the shape of the axial compressor blades using neural networks (artificial neuron network) are shown.

The papers (Sonoda et al., 2014; Zhaoyun et al., 2016) show the examples of the optimization problem using the particle swarm optimization method. This is a computational method that optimizes a problem iteratively trying to improve a candidate's solution with respect to a given quality score. During optimization with the swarm method, an initial set of solutions is formed, called particles, which move around the project space based on the simple formulas. The movement of particles obeys the principle of the best position found in this space, which constantly changes when particles find more favorable positions.

Also, commercial optimization packages are used in several studies. In (Ling et al., 2014) the iSight package was used. The examples of using the IOSO optimization program (IOSO, 2020) are shown in (Marchukov et al., 2019; Vinogradov et al., 2018). In several works, researchers use in-house codes (Kuzmenko et al., 2007; Kröger et al., 2012; Aulich et al., 2013; Komarov et al., 2014).

Summary of the analysis results showed that today there is no unequivocal opinion on which method is best suited for optimizing the MACs. The choice of the method is often based on the traditions

of the research team and affordable software. Moreover, the following general elements can be distinguished in all optimization algorithms found during the review:

- a parameterization component used to create a geometric model of the blades and blade rows based on a set of variable parameters;
- a component intended for the automated creation of a FV model of the MAC flowpath with a modified geometry;
- component of the mathematical model of the MAC workflow, which is used to determine the parameters of interest for the investigated object.

In all studies, it is noted that for successful optimization, all these components must be combined into a single computational algorithm.

It was also noted that only one or two blade rows are considered in most works on the optimization of axial compressors, which indicates the difficulties encountered in the application of optimization methods for the entire flowpath of the MAC and confirms the relevance of the work.

### 3 PARAMETRIZATION OF COMPRESSOR BLADE PROFILES

One of the key technologies of the multicriteria optimization method for the MAC flowpath elements is parameterization of the blade shape. Hereinafter, parameterization refers to a set of independent variables that fully describe the shape of the blade profile of in conjunction with the algorithm for its construction.

The authors of the article developed and implemented their own method of parameterizing compressor blades. It is carried out in 2 stages (Figure 1, Table 1).

At the first stage, a description of the shape of the planar control sections (cylindrical or conical sections, the rotational axis of which coincides with the rotational axis of the turbomachine) is performed in the *Profiler* program (Dmitrieva ana Shabliy, 2014). It was developed at the Department of Aircraft Engine Theory of Samara National Research University (Samara University, 2020). This program can convert the coordinate table, which in the design drawing describes the shape of the blade, into text files of the initial data for constructing design models of turbomachines in the *NUMECA* and *TurboGrid* programs. The *Profiler* also can change the shape of the midline, the stagger angle of the profile, and several other important characteristics of the shape of the blade profile (Dmitrieva ana Shabliy, 2014). The appearance of the *Profiler* interface is shown in Figure 2.

The second stage of parameterization is carried out in the *Profiler 3D* program developed by the authors of the article (Popov, et al., 2017). It can perform the followings:

- change the relative position (shifts in axial, radial and circumferential directions) of the control sections of the blade based on the selected stacking law of the sections along the blade height;
- scale the thickness and chords of the cross sections of the blade by correcting the laws of change in scaling factors along the height of the blade.

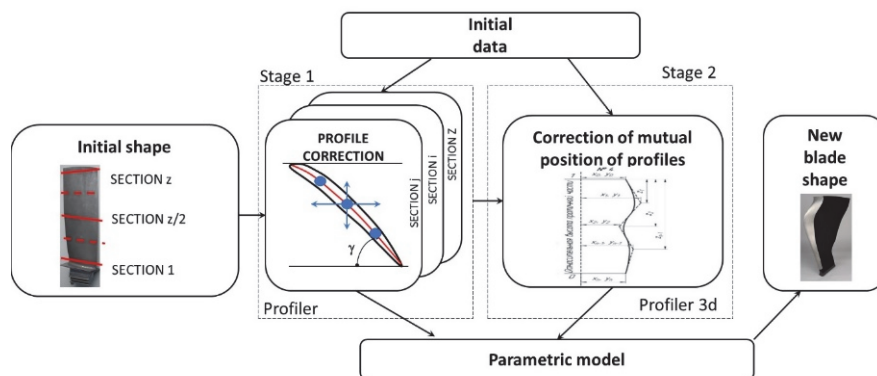


Figure 1: Schematic diagram of the created parameterization scheme.

Table 1: Parameterization stages and their characteristics.

Stage	1	2
Implemented in the program	Profiler	Profiler 3D
What changes at the stage?	<ul style="list-style-type: none"> <li>– Stagger angle of the middle line</li> <li>– Position of the control points on the middle line</li> </ul>	<ul style="list-style-type: none"> <li>– Shift of individual sections in the axial and circumferential direction</li> <li>– Scaling of the profile chord</li> <li>– Scaling of the profile thickness</li> </ul>
How is the pattern of shape change set?	The coordinates or parameters of each corrected section and the midline points are directly changed	The dependence of the change of the adjusted parameter along the blade height is set and the parameters of the control points of the dependence are modified

The algorithm underlying the *Profiler 3D* was built considering the characteristics of the compressor workflow. It is well known that the flow in the blade row has a complex spatial nature, and depends on the loading of the blade rows, which can be different for different stages. Therefore, the parameterization scheme was chosen based on physical ideas about the flow structure in blade rows, so as to be able to purposefully influence the shape of the blades in the characteristic areas of the blade passages: in the flow core, near the endwall regions of hub and shroud.

The second feature is that the number of blade rows in the MAC can be large and exceed the value of 30. Considering that the number of variable parameters during the optimization process is usually limited, the selected parameterization scheme for the MAC blades provides the user with the opportunity to change the number of variable parameters per one row depending on the dimension of the task.

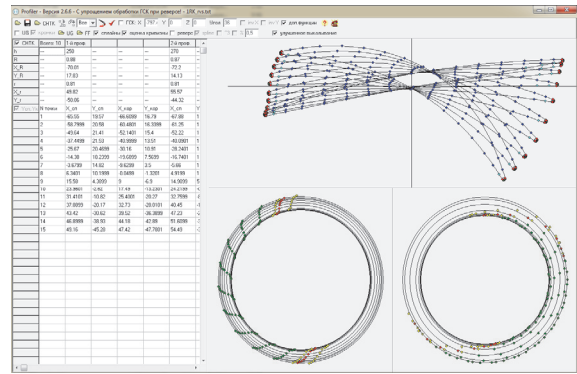


Figure 2: Profiler software.

The main idea of a parametric description of the relative position of the sections along the blade height, implemented in the *Profiler 3D*, is to use the dependence of the variable parameter distribution along the radius  $x_i=f(r)$  (for example, the displacement of the section along the coordinate axes) (Figure 3). The linkage changes by correcting the value of the variable in the control points of the dependence  $x_i=f(r)$ .

In the developed program, the user can fundamentally change the law of distribution of parameters along the radius by choosing the number of control points on the dependence  $x_i=f(r)$ . In principle, the following laws can be implemented (Figure 3):

- linear – by two control points (shroud and hub);
- dependence of degree 2 – by three control points (shroud, hub and intermediate);
- dependence of degree 3 – by four control points (shroud, hub and two intermediate);
- dependence of an arbitrary degree (with an arbitrary number of control points).

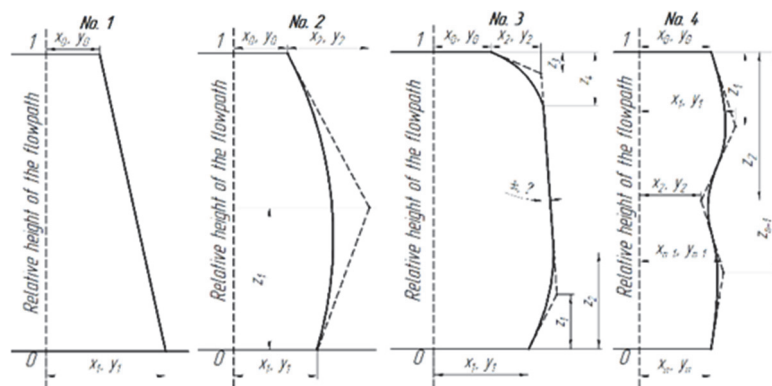


Figure 3: Different ways of describing parameter changes along the radius in Profiler 3D.

The values of variables in arbitrary points of the dependence  $x_i=f(r)$  are calculated by the equation of a polynomial of the corresponding degree (Flanders, 1973). The patterns of parameter changes along the radius can be different for different rows of the same MAC.

The fundamental choice of parameter changing law (the number of control sections) along the height of the blade gives the user an effective tool to reduce the number of variables describing the shape of the profile. As the law becomes more complicated, the user gets more flexibility during optimization, which will help to achieve a better result, but the required number of variables for describing the profile increases significantly. The impact on the radial position of the control points can adjust the degree of deformation along the blade and change the blade to a greater extent where it is really needed (differently in the core and near the endwall regions).

The law of scaling the chords and thicknesses of the blade profiles is set similarly to how the sections are aligned along the blade height.

A coupling of Profiler and Profiler 3D programs (Figure 1) receives the value of independent variables as the input describing the shape of the blades in accordance with the accepted parameterization schemes. As a result, files are generated for each row that describe the geometry of the blades in the *.geomturbo* format adopted in the NUMECA AutoGrid 5 (Numecca AutoGrid, 2020). There, a mesh of finite volumes for the new flowpath is generated. The same program can adjust the axial position of the rows relative to each other, as well as to set, if necessary, a circumferentially variable pitch of the blades. In the process of optimization, the required values of the displacement of the blades in the blade rows are automatically calculated by a special macro and recorded in a script executed during the optimization process.

#### 4 MULTI-STAGE COMPRESSOR OPTIMISATION ALGORITHM

Based on the literature review and practical experience, an algorithm for multicriteria optimization of the shape and relative position of the MAC blades using commercial optimizer and numerical parametric 3D model of its workflow was developed. The algorithm was implemented based on the Numeca software system (Numecca FineTurbo, 2020) and the IOSO optimizer program (IOSO, 2020)

using in-house programs described above (Dmitrieva and Shabliy, 2014; Popov et al., 2017).

Any mathematical optimization algorithm or commercial program can be used for the optimization. The developed algorithm is universal and the choice of the best mathematical method for finding the optimum function is not the goal of this study. The authors of the article tested their algorithms using the IOSO program available on the market. Its choice is due to the large number of results of its successful application in the tasks of aircraft engine building, including by the team of authors of the article (Marchukov et al., 2019; Vinogradov et al., 2018; Popov et al., 2018; Popov et al., 2016; Popov et al., 2019; Baturin et al., 2017). The specified program was used as a finished commercial product. No upgrades were made to the optimization algorithms. A description of the algorithms used in the program can be found on the website and publications of the program developer (IOSO, 2020).

The flow chart of the algorithm is shown in Figure 4. The task of optimizing the MAC is solved iteratively. Before the optimization, variable parameters are set (usually this is the blade geometry using the parameters specified in Section 2), their ranges, criteria (usually the pressure ratio, efficiency, working fluid flow rate or the stability margins) and constraints (strength, structural or technological). The adopted set of variable parameters ensure complete change of the shape of the blade (angles, thicknesses, the shape stacking line of profiles in the radial direction).

The optimization cycle is implemented in the following sequence. Initially, the optimization program (for example, IOSO), based on a list of variable data and a special mathematical algorithm, generates a vector of variable parameters  $x = (x_1, \dots, x_n)$ , which represents the values of the variables of the blades' parametric model and their relative position for the formed variant of the MAC. The values of the vector of variable parameters are automatically written to text files, which are used as initial data for the programs for parametric construction of blade rows Profiler and Profiler 3D (see section 2). These programs generate files with the geometry of the blades in the *.geomturbo* format, which are then transferred to the NUMECA AutoGrid 5, where the FV grid is created (in accordance with the recommendations of Section 3).

Then, the MAC workflow is calculated for one or more operating modes in the CFD software NUMECA FINE/Turbo. It should be noted that the compressor workflow is calculated using a joint model that considers all stages at the same time and



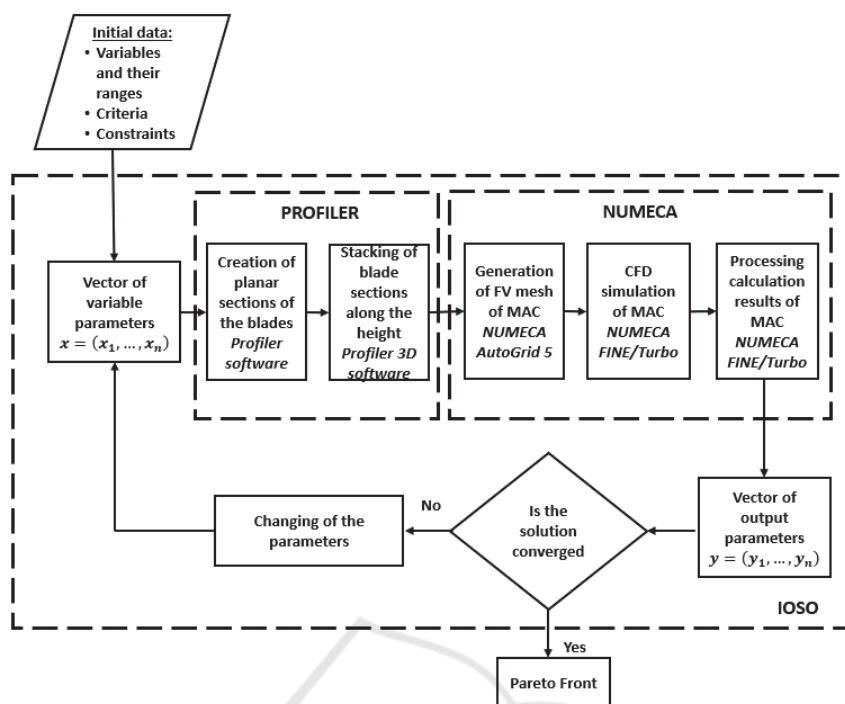


Figure 4: Flow chart of the developed optimization algorithm.

their mutual influence. If the configuration proposed by the optimizer does not work stably for some reason, the CFD solution does not converge at this point and this was considered when the optimizer is working.

At the end of the calculation, a text file is formed with the values of the relevant compressor operation parameters. The values of these parameters determine the vector of output parameters  $y = (y_1, \dots, y_n)$ , which is automatically transferred to IOSO. The vector of output parameters may contain the values of the integral parameters of the flow, for example, the flow rate, the values of pressures and temperatures in the cross sections of the MAC flowpath, as well as complex parameters determined by mathematical expressions based on the integral parameters of the flow, for example, the margin of gas-dynamic stability, the efficiency of the MAC. In IOSO, an analysis of the obtained compressor variant and its saving in the search history of the problem are performed based on a distinctive mathematical algorithm. As a result of the analysis, a front of Pareto-compromise solutions is formed (particular solutions in which an improvement of one of the criteria cannot be achieved without deterioration of the others) among the best MAC variants that satisfy the given constraints, and also a vector of variable parameters for a new iteration is created.

The developed optimization algorithm has been repeatedly tested by the authors in solving various industrial problems. A brief description of some tasks, as well as links to publications that describe them in detail, are given in Table 2.

## 5 CONCLUSION

The paper describes an algorithm developed by the authors for finding the optimal configuration of the blades of multistage axial compressors using 3D CFD modeling as the main tool and using commercial optimization programs. An important element of the algorithm is the original way of parameterizing the shape of the blades and the program based on it, which allow to automatically change the shape of the axial compressor blades. They were used as an important part of the optimization algorithm as a tool that converts variable parameters into the “new” blade geometry. The created algorithm for searching for the optimal shape of the compressor blades can be used to improve the basic parameters of its operation (efficiency, pressure ratio, flow rate, etc.) by correcting the shape of the profiles of the blades and their position relative to each other. In this case, the method takes into account the possible presence of various constraints.

Table 2: The results of some optimization tasks solved using the developed algorithm.

Example	1 (HPC)		2 (LPC)	3 (Three-spool compressor)
Number of optimized parameters	1	2	2	Number of optimized parameters
Number of constraints	no	4	3	Number of constraints
Number of variable parameters	3	15	61	Number of variable parameters
Variable parameters				
Stagger angle of the entire blade	+	+	-	Stagger angle of the entire blade
Stagger angles of individual profiles	-	-	+	Stagger angles of individual profiles
Position of the points of the profile middle line	-	-	+	Position of the points of the profile middle line
Shift of individual section relative to the initial position	-	-	+	Shift of individual section relative to the initial position
Chord scaling	-	-	-	Chord scaling
Blade thickness scaling	-	-	-	Blade thickness scaling
Results				
Efficiency increase	0.3% at 100% mode	1.2% at 95% mode and 0.5 at 100% mode	1.3 at 100% mode	Efficiency increase
Change in the pressure ratio	-	no	+4% (according to the task)	Change in the pressure ratio
Change in stability margins	no	no	no	Change in stability margins
Change in mass flow rate	-3%	no	- 8 % (according to the task)	Change in mass flow rate
Reference	Marchukov, 2017		Goryachkin, 2015	Popov, 2019

The developed optimization algorithm can solve a problem with an unlimited number of variable parameters, constraints and optimization criteria. However, it is obvious that their increase will significantly complicate the search for the optimum and increase (up to the unacceptable) time to search for a solution. However, in practice, the authors did not solve problems in which the number of optimization criteria was more than two (due to the complexity of analyzing the results with a larger number of variables), and the number of variable parameters was not more than 99 (due to limitations of the available license for the IOSO optimizer program).

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