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# APPLICATION OF OPTIMIZATION METHODS IN TURBOMACHINERY DESIGN

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**Abstract-** Modern computer technologies now allow us to conduct rather complex mathematical calculations in a relatively short period of time. Thus, it has become possible to employ optimization methods in the design of various parts of aircraft engines, even when calculations require large computational resources (structural, thermal, and gasdynamics calculations).

The designer may have to vary more than a hundred design variables and constraints during the optimization process. Therefore the procedure of preparing the initial data for optimization may take a long time. That is why we developed the optimization software system for designing turbomachines and their parts. This software system includes the IOSO optimization procedure and modules of automatic data preparation and handling. The data is represented in the format that is convenient and understandable for a designer.

The optimization procedure is based on the response surface methodology, when response surfaces are constructed for objective functions and constraints and then optimized at each iteration in a current search region. The objective function and constraints are then evaluated at the optimal point using the mathematical model of the system under consideration.

In this paper we presents 2 examples of real-life problems. The first one is connected with the search for the optimum geometry for the rotor of an up-to-date fan. The goal of the research was to ensure the highest strength indices of the rotor. The multi-objective approach was used to solve this task (5 objectives). As the analysis the ANSYS software code was used, while the search for the optimum solutions was carried out using the IOSO NM algorithm designed for parallel multi-objective optimization within the frameworks of IOSO Technology. As a result, the improvement in all the strength indices was obtained (from 9 to 56 % as compared with the prototype).

The goal of the second optimization problem was to increase the efficiency of the fan rotor in the given point of its characteristics considering the splitting of the flow into core and bypass ducts. The peculiarity of this problem was the necessity to keep the strength constraints (multidisciplinary approach). To solve this problem, a 3-D CFD code and multilevel algorithm of IOSO technology was used. The search for the optimum was carried out in the multi-objective statement (the compromise between the efficiency levels for core and bypass contours was searched). The optimization research allowed the rise of the fan rotor efficiency by more than 1.5%.

## 1. INTRODUCTION

The design of modern compressors is a very complex task, since it takes into account a large number of efficiency parameters and constraints which are being viewed from different scientific angles. An extensive use of modern numerical design methods combined with highly efficient optimization techniques, can substantially reduce the time and cost of the design.

In spite of the similarity of approaches to the solution of problems of nonlinear programming, the optimization of compressors and its elements has its own specific features. First, due to contradictory requirements for the compressor, it is of practical interest to search for the extreme and compromise values of the whole set of efficiency factors: air flow, engine pressure ratio, gas-dynamic stability margin in different operation modes, various strength characteristics. From this point of view, optimization represents a multi-objective problem. When solving real-life tasks, designers usually pick up one or several of the most important efficiency characteristics. The solution is searched on a limited area determined by various gas-dynamic, kinematical, constructional, technological, etc. parameters. On the whole this comes down to a single- or multi-criteria constrained optimization problem.

Second, the optimization criteria and constraints in a particular problem are defined by the mathematical modeling of the compressor operation. In order for the results to have practical importance, it is necessary that the model can describe processes with a required extent of adequacy and reliability. These days a number of different models are used: from simplified ones to those based on numerical calculation of Navier-Stokes three-dimensional equations (CFD codes) for flow analysis and finite-element investigation for strength analysis.

Third, the geometry of modern processors is usually developed in special (CAD) software and it involves a great number of parameters. To perform an optimization process, the compressor geometry should be described by a minimal set of parameters (vectors of variable parameters). It is necessary that special procedures of compressor parameterization be developed. The problem of optimization of a compressor and its elements may have a large number of variable parameters (since the researchers seek to achieve a maximum possible effect). Today, for a multi-stage axial compressor the typical number of variables may be tens or even hundreds. The larger the number of variables in the optimization process, the more efficiency gain can achieved.

Fourth, problems of the compressors optimization may belong to different classes (with smooth, non-differentiable, stochastic, etc. objective functions), when the topology of the objective function and constraints at the stage of the problem statement being, as a rule, unknown. When solving optimization tasks of different classes, the best way will be to use specialized nonlinear programming methods. The problem of choosing an optimization technique is a difficult one.

Fifth, obtaining of the extremum value may take a considerable amount of computational time, as much as several months. The time is directly linked with the level of the compressor simulation, with the number of variables in the optimization task, with the topology of the objective function, etc.

This work is aimed at demonstration the possibilities of IOSO optimization technique when used in combination with well-known commercial software applications for the design of modern compressors. These possibilities are demonstrated in two examples: the optimization of an axial fan impeller by gas-dynamic and strength characteristics. The multi-criteriality of these tasks is their distinctive feature.

## 2. FEATURES OF THE IOSO TECHNOLOGY ALGORITHMS

The multi-objective optimization problem minimizes a vector of $m$ objective functions, namely

$$\min_{\bar{x}\in D} \tilde{y}_i(\bar{x}) \quad for \quad i=\overline{1,m}. \tag{1}$$

A correct multi-objective problem statement is possible on the basis of the optimality concept formulation. In most technical multi-objective problems, the Pareto-optimality concept is used [4]. According to this concept vector, $\bar{x}^p$ - is Pareto-optimal ($\bar{x}^p \in P$) if $\bar{x}^p \in D$ and does not exist such the $\bar{x} \in D$, that $\tilde{y}_i(\bar{x}) \le \tilde{y}_i(\bar{x}^p), \forall\ i=\overline{1,m}$ even if one of these inequalities is rigorous. In this case, the multi-objective optimization problem involves the determination of a full set of Pareto-optimal points.

As a rule, it is impossible to find the full infinite set of Pareto-optimal points when solving realistic problems. For this reason the engineering statement of a multi-objective problem consists of the determination of a finite subset of criteria-distinguishable Pareto-optimal points. Thus, it is required to find all the elements of the set $A \in P$, such that for any two vectors $\bar{x}_j \in A$ and $\bar{x}_k \in A$:

$$\sum_{i=1}^{m} \left| \tilde{y}_i\left(\bar{x}_j\right) - \tilde{y}_i\left(\bar{x}_k\right) \right| > e,\ j \ne k \tag{2}$$

The parameter $e$ of the Pareto-optimal points distinguishability is specified by the designer. The number of distinguishable Pareto-optimal points depends on the value of the distinguishability parameter $e$ and topological peculiarities of the goal functions and constraints.

Every iteration of the IOSO algorithm consists of two steps [1]. The first step is the creation of analytical approximations of the objective functions. Our approach is based on the widespread application of the response surface technique, which depends upon the original approximation concept. According to this concept we use adaptively global or middle-range, multi-point approximation. One of the advantages of our approach is the possibility of ensuring good approximating capabilities using the minimum amount of available information. This possibility is based on self-organization and evolutionary modeling concepts [2]. During the approximation, the approximation function structure is being evolutionarily changed, so that it allows for the successful approximation of the goal functions and constraints having sufficiently complex topology.

As a rule, it is impossible to correctly specify the parameter of Pareto-optimal points distinguishability, $e$, from the beginning. For this reason the designer specifies the desired number of Pareto-optimal points, and the parameter $e$ is adaptively changed during optimization to achieve this desired number of solutions uniformly distributed in objectives space.

The main advantages of this algorithm over traditional mathematical programming approaches are the following:

- convolution approaches are not used in solving multi-objective problems;
- the algorithms determine the desired number of Pareto-optimal solutions, so that these solutions are uniformly distributed in the space of objectives;
- it is possible to solve the optimization problems for the objective functions of complex topology: non-convex, non-differentiable, with many local optima;
- it is possible to naturally employ the parallelization of the computational process.

These advantages are the basis for the wide use of the various modifications of this method in the real-life problems.

The software and tools of the IOSO Technology consist of several independent algorithms. All IOSO technology algorithms were developed according to the single concept of formulating optimization problems, providing initial data, data exchange with the user's program, and the analysis of the obtained results. IOSO technology algorithms are practically insensitive with respect to the types of objective function and constraints: smooth, non-differentiable, stochastic, with multiple optima, with the portions of the design space where the objective functions and constraints could not be evaluated at all, with the objective function and constraints dependent on mixed variables, etc.

The flexible structure of IOSO main algorithm provides wide opportunities concerning the development of new approaches aimed at the reduction of the computing time for complex real-life problems. In the present paper we analyze two possible approaches. One of them utilizes parallelization of computations during an optimization problem solution. The other is based upon the use of mathematical models with different accuracy levels [3].

## 3. OPTIMIZATION OF FAN STRENGTH CHARACTERISTICS

### 3.1. PROBLEM STATEMENT

In this work an optimization of the static strength characteristics of a fan impeller was performed by offsetting the main points of the plane sections.

The task was to reduce the maximum values of the tensions and deformations of the fan blade when transferring to the "hot state". The variable parameters were the values of the offsets of the main points of plane sections in 7 sections along the fan blade. The following optimization criteria were used (Figure 1):

- maximum value of the tension in the blade of the impeller (*Sig*);
- deformation in the radial direction (*Ux*);
- deformation in the tangential directions along the front and back edges (*Uyin*, *Uyout*);
- The extent of the "symmetry" of deformations along the front and back edges ($|Uyin + Uyout|$).

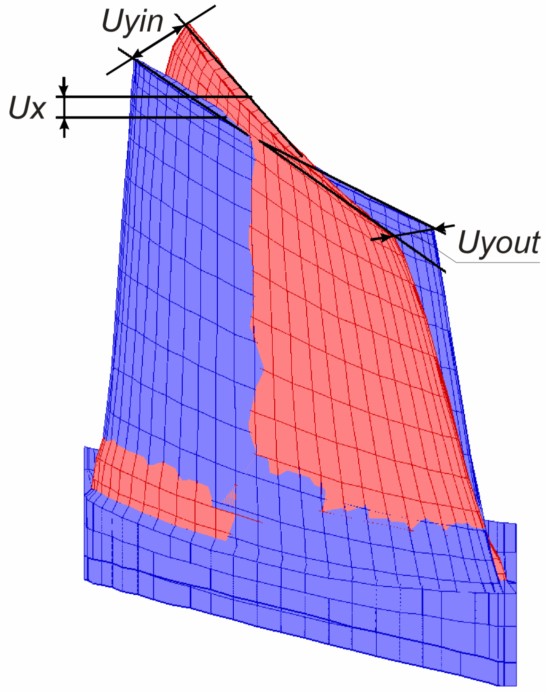

Figure 1. Possible deformations in the radial and tangential directions.

Thus, for the problem considered, there are 7 independent variables and 5 optimization criteria. In addition, 5 criterion constraints representing "non deterioration" of the parameters of the initial project are introduced.

The main feature of this problem is the presence of a database with results of a preliminary design. The database contained 20 points, only one point corresponding to the blade being reviewed (reference design), the other 19 were obtained for the prototype of the given blade. To reduce the time needed for optimization, we used an existing database in the approximation algorithms of IOSO technology. The problem was solved with the use of the parallel multi-objective IOSO technology optimization algorithm.

## 3.2. MAIN RESULTS

During optimization a total of three iterations of the parallel optimization algorithm of the IOSO technology were performed (6 calculations at the first iteration, and by 8 calculations at the second and third iterations). With the solution of the task, the amount of data used for the approximation of optimization criteria increased, improving the quality of the database owing to the increase in the number of calculations for the fan being optimized. The history of the database change is shown in Figure 2.

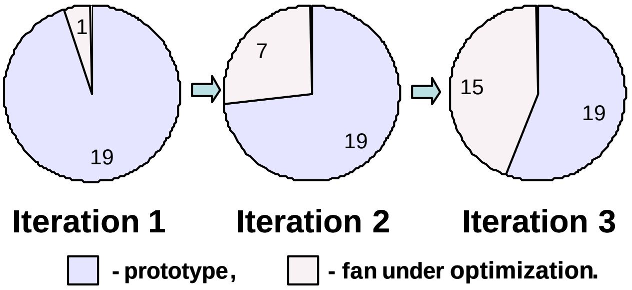

Figure 2. The history of the database content change.

The results for each iteration are shown graphically in Figures 3, 4 and 5 (the results are presented in relation to the initial project; if a relative number exceeded the value of 2.0, it was set to be 2.0). Figure 6 shows in more detail the results for the best project (Var. 3.8). It can bee seen that the given project makes it possible to improve all the optimization criteria simultaneously, the extent of the improvement of the partial criteria being between 9 and 56%. Figure 7 shows stress distribution in the blade of the fan impeller for the initial and optimal designs.

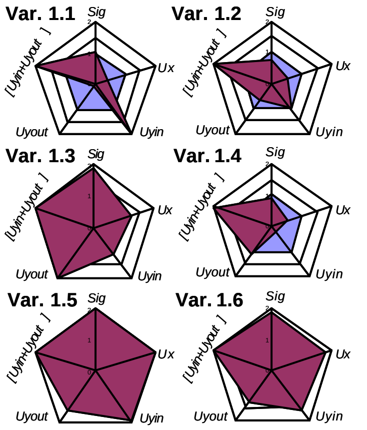

Figure 3. Results of first iteration.

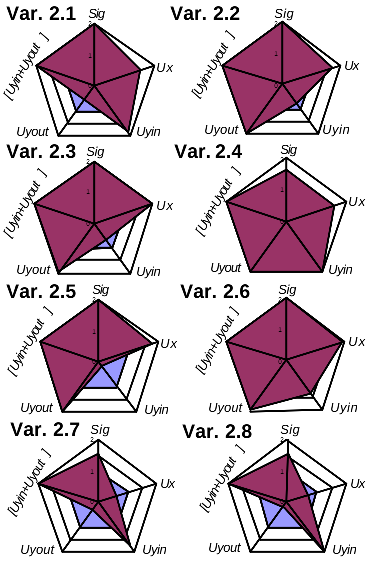

Figure 4. Results of second iteration.

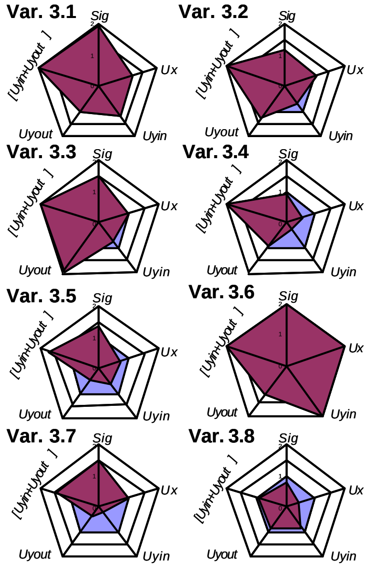

Figure 5. Results of third iteration.

It is important, from a mathematical point of view, that the solution of the multi-objective problem should be a set of Pareto-optimal projects, from which the designer can choose some compromise option. However, to obtain such a set a great number of calculations should usually take place. When solving practical tasks the designers can interrupt the process of optimization if a desired compromise has been reached. In this case the last project (Var. 3.8) met all desired requirements and was accepted to be optimal.

Thus, in the described case the solutions were obtained in as few as three iterations in the optimization process, with the total number of calculations being 22. This is an indication of the high efficiency of the IOSO optimization technique.

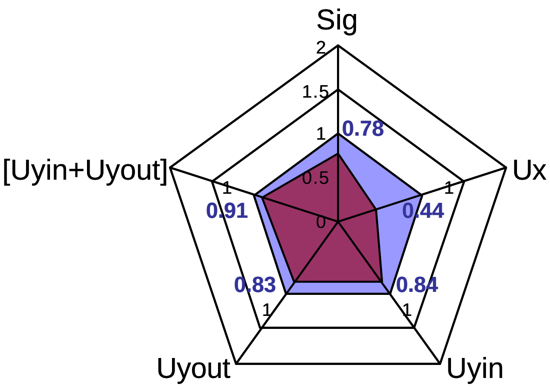

Figure 6. Optimal project (variant 3.8).

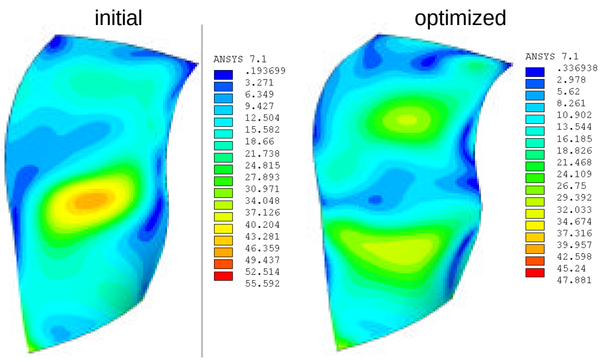

Figure 7. Stress distribution in blades of the fan under optimization.

## 4. OPTIMIZATION OF THE FAN GAS-DYNAMIC CHARACTERISTICS

### 4.1. PROBLEM STATEMENT

In this work an optimization was performed for the gas-dynamic characteristics of the fan impeller with a high bypass ratio. The main features of this problem were as follows:

- High level of efficiency of the initial project (prototype) and the presence of fairly strict constraints for the air flow and pressure ratio.
- The necessity to search for possibilities of the increase in efficiency of the fan impeller for both external and internal contours.

The formal problem statement consists in the search of the set of Pareto-optimal projects, satisfying:

$$h_I^*, h_{II}^* \to max;\ \ p_I^* \ge p_{Ipre}^*,\ p_{II}^* \ge p_{IIpre}^*;\ \ G_{max-} \le G_{max} \le G_{max+},\ G_{ef-} \le G_{ef} \le G_{ef+},$$

where: $h_I^*, h_{II}^*$ - are the isentropic efficiency of fan impeller for internal and external contours respectively; $p_I^*, p_{II}^*$ - are the pressure ratio for internal and external contours respectively; $G_{max}$ - is the maximum airflow through the fan impeller; $G_{max-}, G_{max+}$ - are the minimum and maximum acceptable values of the airflow through the impeller; $G_{ef}$ - is the airflow through the impeller at the point of maximum efficiency; $G_{ef-}, G_{ef+}$ - are the minimum and maximum acceptable values of the airflow through the impeller at the point of maximum efficiency; the *'pre'* index means a set value of the parameter being considered, corresponding to initial variant of the impeller. Figure 8 shows graphical illustration of the problem statement.

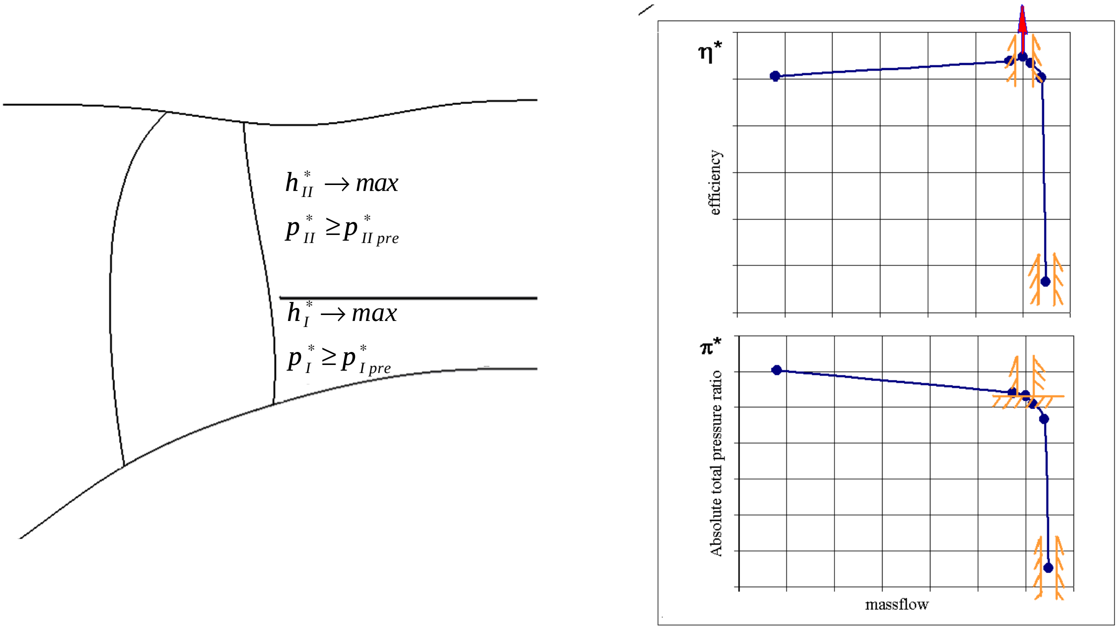

Figure 8. Optimization problem statement.

When developing a parameterization scheme, we pursued two main goals:

- Adaptability in the manufacture of the fan blade. Proceeding from this, a solution was searched within the class of symmetrical profiles by varying the position of the centerline of the profile.
- Minor alteration in the strength characteristics of the blade. Proceeding from this requirement, thickness of the profile was kept constant.

Figure 9 shows the accepted scheme of the impeller parameterization. It can be seen that the variation of the position of the profile's centerline was done in 5 control points on each of 6 sections radially. As a result, the number of variable parameters was 30. The blade face is outlined by Bezier curves.

When solving optimization problems with 3D CFD codes it is important that a reasonable analysis grid is chosen. Preliminary research showed that the calculation of the flow in the fan impeller with sufficient accuracy is possible with the grid of 1.536.000 knots. The average time for the calculation of one design of the geometry takes about 9 hours on a P-IV 3.0 Ghz computer. To reduce the amount of time for the optimization, it was decided to use a multilevel IOSO technology optimization algorithm. At the same time, at an initial stage the optimization calculations were done with a "rough" grid (430.000 knots, average computing time is 3 hours). The optimization criteria included not only the efficiency for the first and second contours ($h_I^*, h_{II}^* \to max$) but also the corresponding number of pressure ratios ($p_I^*, p_{II}^* \to max$). After the preliminary stage, 50 variants of the geometry with uniformly distributed in the space of criteria were picked up; calculations with a "good" grid were carried out; then the optimization process continued.

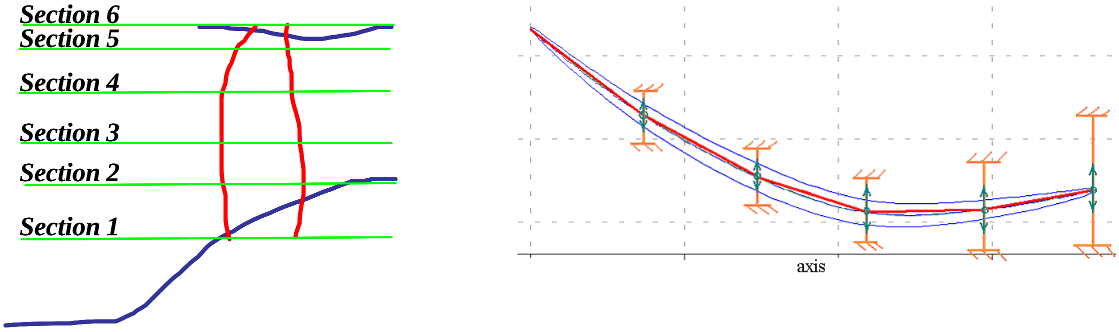

Figure 9. Fan blade parameterization.

### 4.2. MAIN RESULTS

At a preliminary stage of the optimization, 29 iterations according to the IOSO parallel optimization algorithm were performed with the use of a "rough" computational grid (30 calculations for each iteration); and then 5 more iterations with the use of a "good" grid. It is important to note that at the initial stage of the optimization there were many cases when for the given vector of the variable parameters it was impossible to perform calculation of optimization criteria and constraints (the crash models). Figure 10 shows how the ratio of successful and unsuccessful calculations changes as the optimization problem is solved. It can be seen that during the solution process the stability region of the model is being outlined and the number of crashed calculations is being decreased.

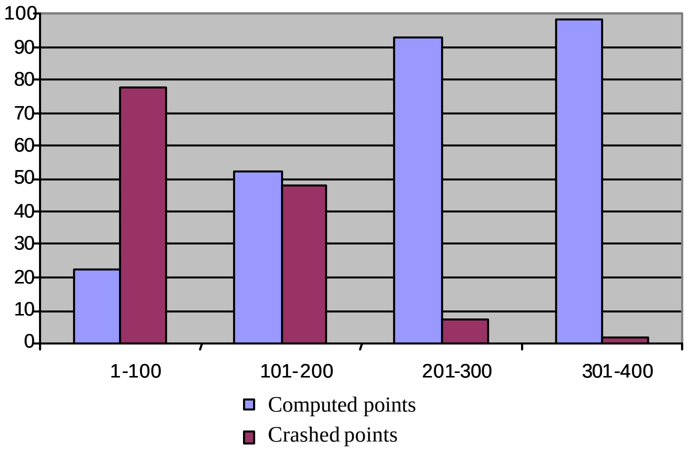

Figure 10. Dynamics of the 3D-CFD module stability while solving the task.

The results of the calculations which use a "good" grid and meet the constraints are shown in Figure 11.

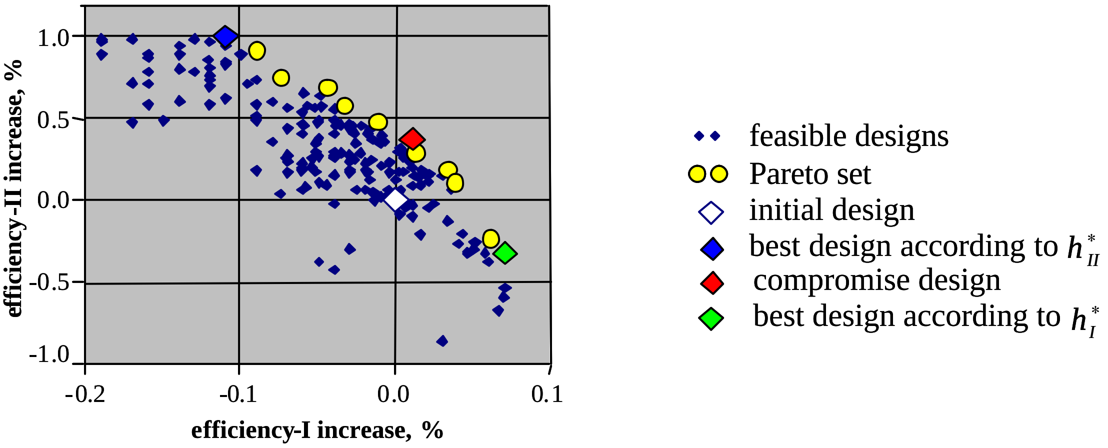

Figure 11. Optimization results.

The analysis of the obtained results shows that despite strict limitations, substantially narrowing of the search area, the problem has a significant area of compromise between optimization criteria. For example a suitable choice of geometry of the impeller made it possible to increase the efficiency on an external contour by about 1% by the decrease in the efficiency of the internal contour by approximately 0.1 %. After the analysis, one of the compromise projects (providing an increase in the efficiency for both external and internal contours) was chosen. Figure 12 shows a distribution of Mach numbers at the periphery of the impeller for the initial and the chosen optimum projects. A slight drop of intensity jump and decrease in the flow separation zone for the optimum project is observed.

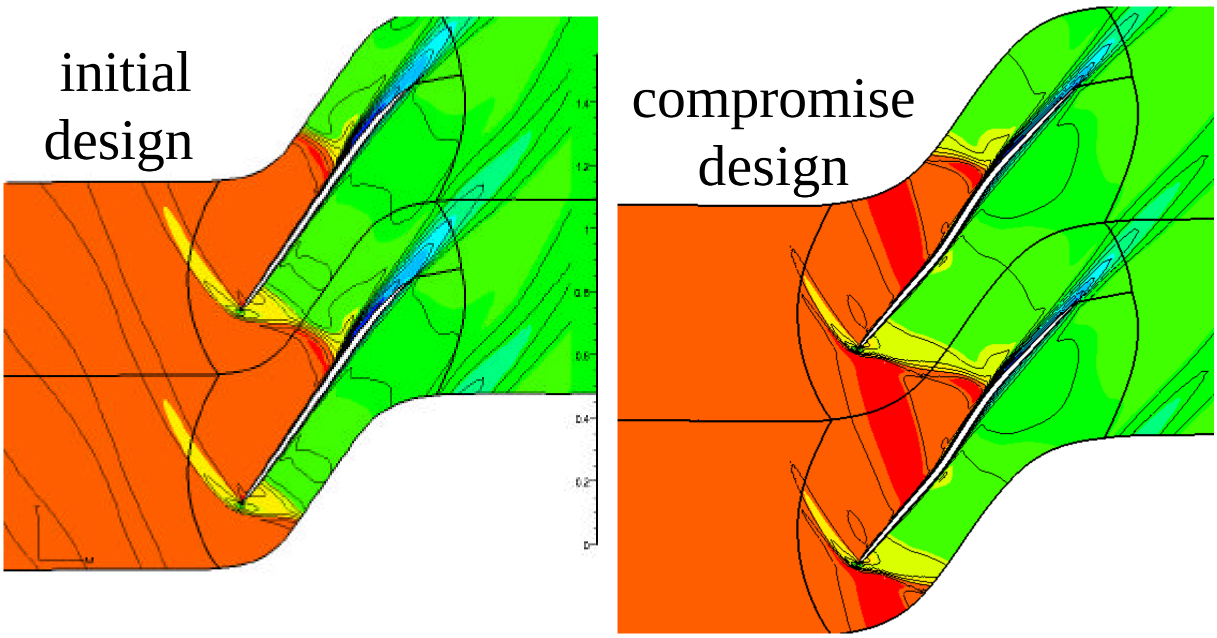

Fig. 12. Comparison of Mach numbers distribution for the initial and compromise designs.

## 5. CONCLUSION

The obtained results indicate the possibility for solving extremely complex problems of the optimization of gas-dynamic and strength characteristics for modern fans with the use of 3D methods and IOSO optimization technology. With all this, a substantial decrease in the optimization time can be achieved thanks to the use of parallel multilevel optimization procedures.

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