INCREASING OF AIR ENGINE EFFICIENCY BASING ON OPTIMIZATION TECHNOLOGY

M.L. Kuzmenko*, I.N. Egorov** and N. Shmotin Yu+

Abstract

At present NPO Saturn possesses the complex of technologies, which allow obtaining the most efficient technical solutions when creating up-to-date gas-turbine engines and their components. In this paper there are presented the examples researches aimed at axial compressors perfection basing on up-to-date analysis and optimization tools. As the analysis tools there are used the well-known commercial software packages (CFX-TASCflow, ANSYS etc.), as well as the models developed by NPO Saturn; the adequateness of latter had been proved by experimental data. To rise the efficiency and margins of gas dynamic stability for multistage axial compressors NPO Saturn is using widely the methods of CFD and optimization based on IOSO technology. In the paper there are presented some examples of real-life problems solution.

Introduction

The design of modern compressors is a very complex task, for 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 non-linear programming, the optimization of compressors and its elements has its own specific features. First, due to contradictory requirements to the compressor, it is of practical interest to search for extremum 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-criteria problem. When solving real-life tasks designers usually pick up one or several 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 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, 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 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 multistage axial compressor the typical number of variables may be tens or even hundreds. The more is the number of variables in the optimization process, the more efficiency gain can achieved.

Fourth, problems of optimization of compressors and their elements may belong to different classes (with smooth, non-differentiable, stochastic, etc. objective functions), when the topology of the objective function and

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* General Designer ** Chief Designer + Deputy General Designer
NPO Saturn, Kasatkin 13, Moscow, 129301, Russia

constraints at the stage of problem statement being, as a rule, unknown. When solving optimization tasks of different classes the best way will be to use specialized non-linear programming methods. The problem of choosing an optimization technique is a difficult one.

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

This work is aimed to demonstrate 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 by two examples: the optimization of axial fan impeller by gas-dynamic and strength characteristics. The multicriteriality of these tasks is their distinctive feature.

IOSO Technology Algorithms Features

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

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

A correct multi-objective problem statement is possible on the basis of optimality concept formulation. In most technical multi-objective problems the Pareto-optimality concept is used. According to this concept vector $\bar{x}^p$ - is Pareto-optimal one ($\bar{x}^p \in P$) if $\bar{x}^p \in D$ and does not exist such $\bar{x} \in D$, that $\tilde{y}_i(\bar{x}) \le \tilde{y}_i(\bar{x}^p)$, $\forall$ i= $\overline{l,m}$ even if one of these inequalities is rigorous. In this case, the multi-objective optimization problem involves 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 in the determination of a finite subset of criteria-distinguishable Pareto-optimal points. Thus, it is required to find all the elements of set $A \in P$, such that for any two vectors $\bar{x}_j \in A$ and $\bar{x}_k \in A$:

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

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

Every iteration of 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, within the frameworks which adaptively use global and 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 ε from the very beginning. For this reason the designer specifies the desired number of Pareto-optimal points, and parameter ε 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.

Software and tools of 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 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 objective function 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].

Optimization of Fan Strength Characteristics

Problem Statement

In this work an optimization of 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 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 (Fig.1):

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

Thus, for the problem considered, there are 7 independent variables and 5 optimization criteria. Besides, 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 approximation algorithms of IOSO technology. The problem was solved with the use of parallel multi-criterion IOSO technology optimization algorithm.

Main results

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

The results for each iteration are shown graphically in Fig.3...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). Fig.6 shows in more detail the results for project No. 3.8. It can bee seen that the given project makes it possible to improve all optimization criteria simultaneously, the extent of improvement of partial criteria being between 9 and 56%. Fig.7 shows stress distribution in the blade of the fan impeller for initial and optimal designs.

It is important that from mathematical point of view the solution of multi-criteria 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 designers can interrupt the process of optimization if a desired compromise has been reached. In this case project No. 3.8 met all desired requirements and was accepted to be optimal.

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

Optimization of Fan Gas-Dynamic Characteristics

Problem Statement

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

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

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

$$\eta_I^*, \eta_{II}^* \to max;\ \pi_I^* \ge \pi_{Ipre}^*, \pi_{II}^* \ge \pi_{IIpre}^*;$$

$$G_{max-} \le G_{\max} \le G_{max+},\ G_{ef-} \le G_{ef} \le G_{ef+}$$

where

η_I^*, η_{II}^* - isentropic efficiency of fan impeller for internal and external contours;

π_I^*, π_{II}^* - pressure ratio for internal and external contours; G_{max} - maximum airflow through fan impeller; G_{max-}, G_{max+} - minimum and maximum acceptable values of airflow through impeller; G_{ef}- airflow through impeller at the point of maximum efficiency; G_{ef-}, G_{ef+} - minimum and maximum acceptable values of airflow through impeller at the point of maximum efficiency; the ‘pre’ index means set value of the parameter being considered, corresponding to initial variant of impeller. Fig. 8 shows graphical illustration of the problem statement.

When developing parameterization scheme we pursued two main goals:

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

Figure 9 shows the accepted scheme of impeller parameterization. It can be seen that the variation of the position of 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 calculation of one design of geometry at that is about 9 hours on P-IV 3.0 GHz computer. To reduce the amount of time for 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 "rough" grid (430.000 knots, average computing time is 3 hours). At that, the optimization criteria included not only efficiency for first and second contours ($\eta_I^*, \eta_{II}^* \to$ max), but also the corresponding number of pressure ratio ($\pi_I^*, \pi_{II}^* \to$ max). After a preliminary stage 50 variants of geometry uniformly distributed in the space of criteria were picked up; calculations with "good" grid were carried out; then optimization process continued.

Main results

At a preliminary stage of optimization 29 iterations according to 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 say that at the initial stage of optimization there were many cases when for the given vector of variable parameters it was impossible to perform calculation of optimization criteria and constraints (the crash models). Fig.10 shows how the ratio of successful and unsuccessful calculations is changed as the optimization problem is solved. It can be seen that as a solution goes on the stability region of the model is defined and the number of crashed calculations decreases.

The results of calculations which use "good" grid and meet the constraints are shown on Fig.11. The analysis of the obtained results shows that despite strict limitations, substantially narrowing 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% at the decrease of efficiency of internal contour by approximately 0.1%. After the analysis one of the compromise projects (providing increase of efficiency for both external and internal contours) was chosen. Fig.12 shows distribution of Mach numbers at the periphery of impeller for the initial and the chosen optimum projects. A slight drop of intensity jump and decrease of flow separation zone for the optimum project is noticeable.

Conclusion

The obtained results indicate the possibility to solve 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 of optimization time can be achieved thanks to the use of parallel multilevel optimization procedures.

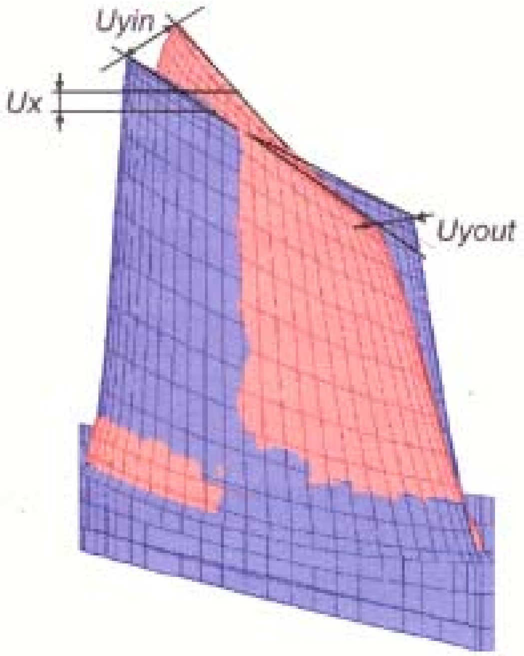

Fig.1 Possible deformations in radial and tangential directions

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2. Egorov, I.N., "Indirect Optimization Method on the Basis of Self-organization", Curtin University of Technology, Optimization Techniques and Applications (ICOTA'98), Perth, Australia, 1998, Vol.2, pp. 683-691.

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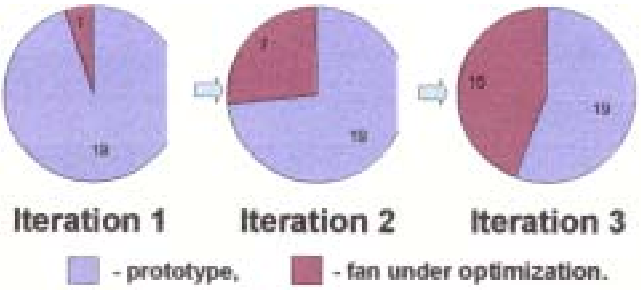

Fig.2 The history of database content change

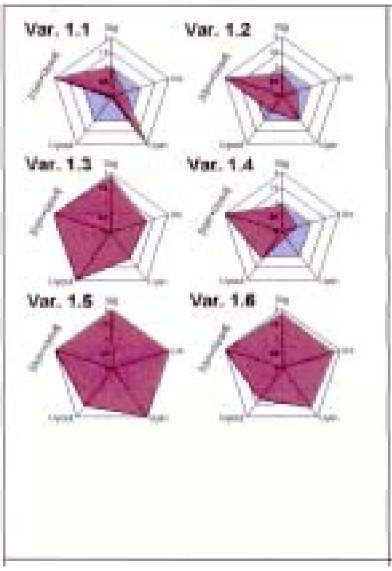

Fig.3 Results of first iteration

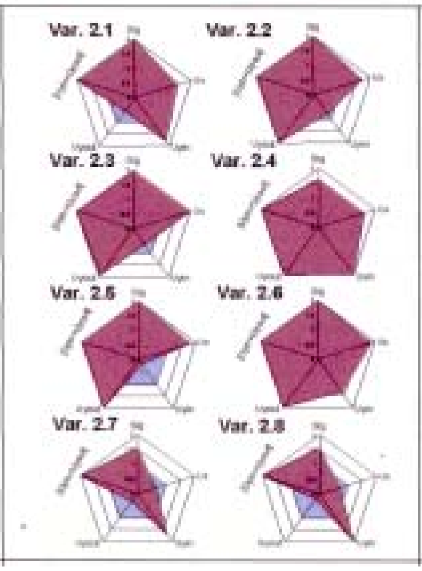

Fig.4 Results of second iteration

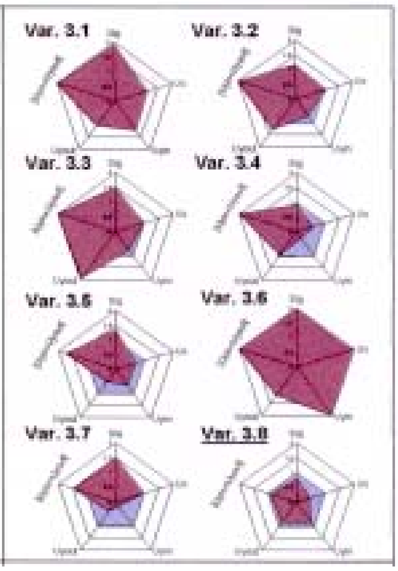

Fig.5 Results of third iteration

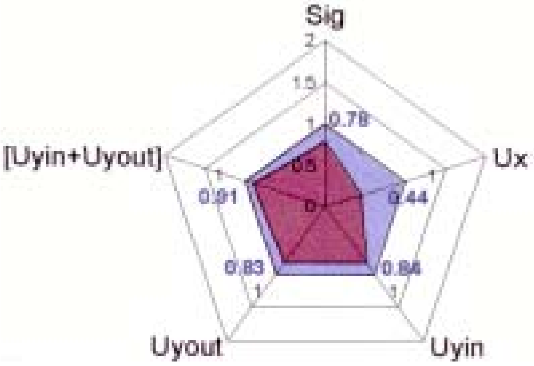

Fig.6 Optimal project (design 3.8)

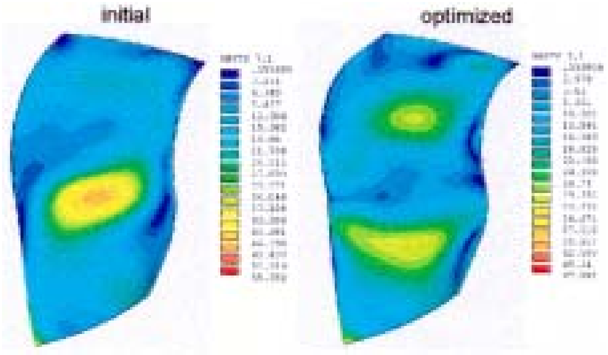

Fig.7 Stress distribution in blades of the fan under optimization

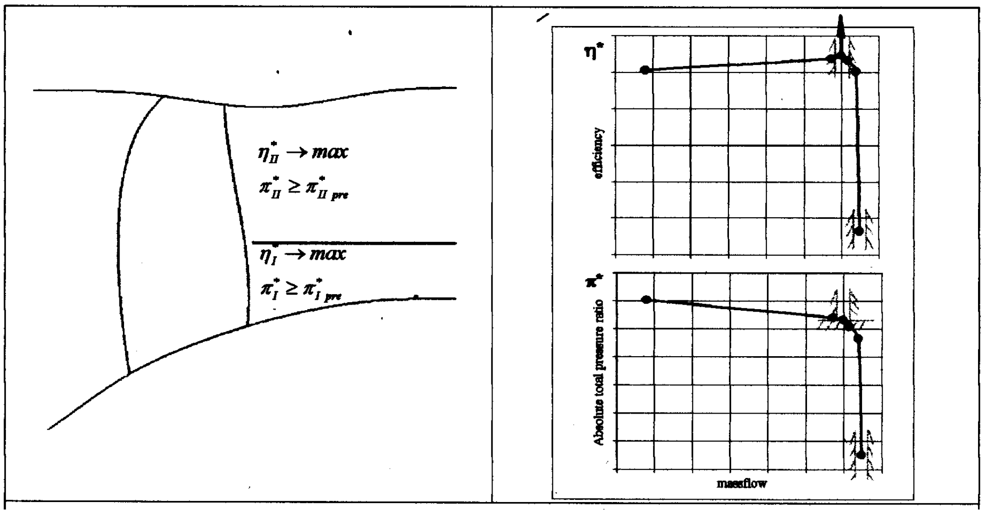

Fig.8 Optimization problem statement

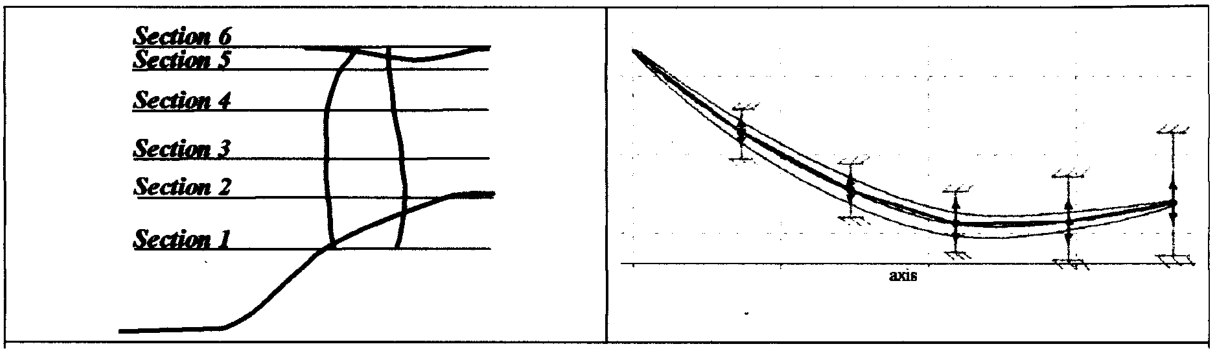

Fig.9 Fan blade parameterization

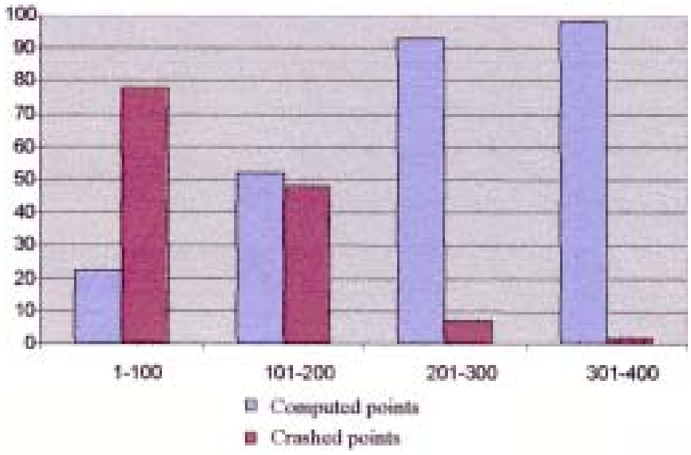

Fig.10 Dynamics of 3D-CFD module stability while solving the task

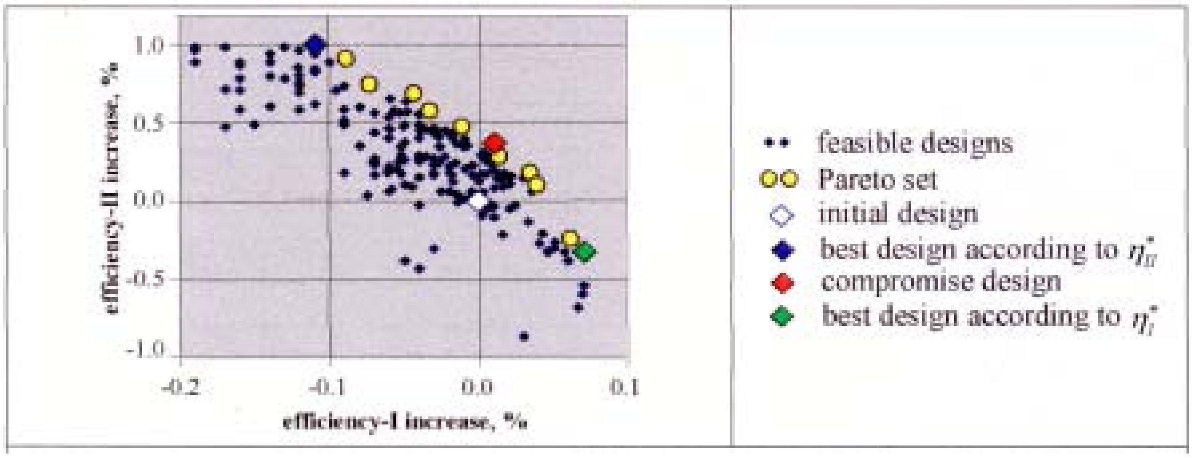

Fig.11 Optimization results

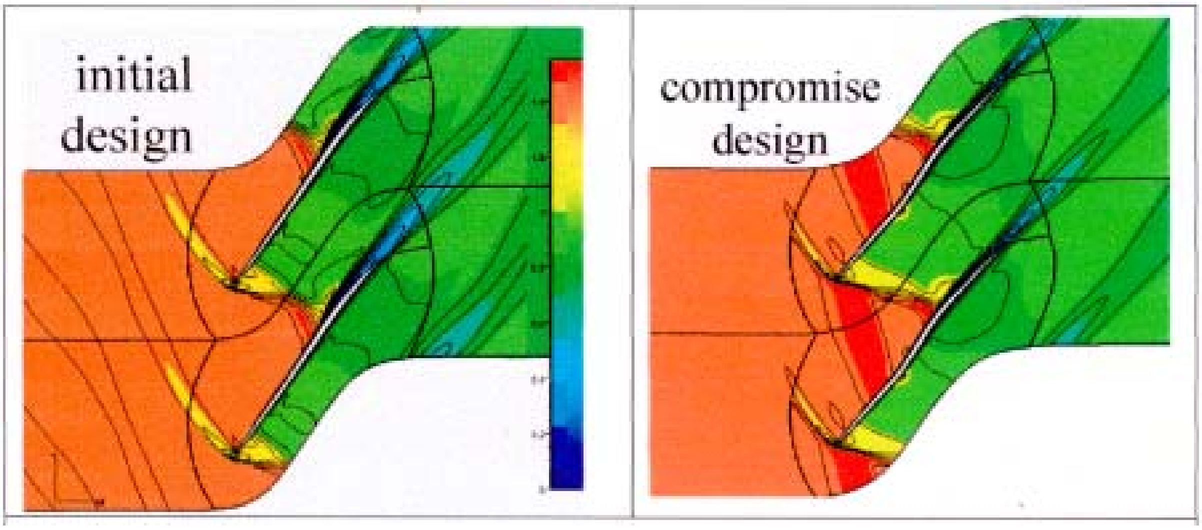

Fig.12 Comparison of day-time picture for initial and compromise designs