

# Numerical design optimization of compressor blade based on ADOP

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**Abstract:** An aerodynamic design optimization platform (ADOP) has been developed. The numerical optimization method is based on genetic algorithm (GA), Pareto ranking and fitness sharing technique. The platform was used for design optimization of the stator of an advanced transonic stage to seek high adiabatic efficiency. The compressor stage efficiency is increased by 0.502% at optimal point and the stall margin is enlarged by nearly 1.0% at design rotating speed. The flow fields of the transonic stage were simulated with FINE/Turbo software package. The optimization result indicates that the optimization platform is effective in 3D numerical design optimization problems.

**Key words:** compressor; genetic algorithm (GA); optimization

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## Introduction

High performance engine strongly affects the performance of aircraft. Improving aerodynamic performance in engine is an important and challenging work for the present and future industry. Design of turbomachinery plays an important role in the engine development and aerodynamic design optimization of turbomachinery blades, still an active research field, is vital to the improvement of performance. Traditional aerodynamic design or redesign of compressor/turbine is mainly based on empirical techniques, as well as the so called 'trial and error' methods, which demands long period, high expenditure and plenty of experience of designers, but do not guarantee optimal designs. With the swiftly development of powerful computer techniques and computational fluid dynamics (CFD),

numerical simulation has becoming more affordable and simulation based optimization is becoming more attractive and more popular than ever.

Development of aerodynamic design methods for turbomachinery is always an interesting topic. Inverse design method has acquired successful applications<sup>[1]</sup>. The approach determines the blade shape from a prescribed velocity or pressure distribution. This is a powerful design method for those with insights who are able to establish an optimum aerodynamic description. The method does not demand iteration between design and redesign, and has high efficiency. But it still has some bad shortcomings, such as difficult to include geometric constraints, difficult to deal with 3D optimization problem, difficult to specify an appropriate pressure/velocity distribution to designers, etc., so it is restricted to be widely employed. Therefore, in this paper, a

direct approach is employed. Direct design method is incessantly to change original geometry according as results of aerodynamic numerical simulation until optimal airfoils with favorable aerodynamic performance. Direct design optimization methods rely less on experience, and can easily be developed to actualize multiobjective optimization<sup>[2-4]</sup>. It can greatly improve the efficiency, reduce the cost and obtain better results, even if the computational cost of optimization can, in many cases, much larger than the cost of an analysis calculation.

## 1 Aerodynamic design optimization platform (ADOP)

As the 3D numerical simulation of flow field requires tremendous computational time, a response surface model (RSM) based on artificial neural network (ANN) was used to approximate the overall aerodynamic performance of the transonic stage. The samples for the response surface was selected with uniform design of experiment (UDOE)<sup>[5]</sup>, which provided smallest quantity of experiment points from large design space.

### 1.1 Numerical optimization method

Numerical optimization methods can be divided into local and global optimization algorithms. Local search algorithms, including gradient based methods, can converge to local maximum with high rapidity and efficiency, but can not insure globality and can not carry through when the design space is discontinuity. On the contrary, global search methods such as genetic algorithms (GAs) offer an alternative approach with several attractive features. Firstly, GAs are insensitive to design space, work well in non-smooth design spaces containing multiple local extrema. Secondly, GAs can easily include constraints. Thirdly, GAs can be efficiently parallelized. Finally, GAs can search for Pareto optimal solutions in parallel by maintaining a population of solutions and can directly approach multiobjective optimization problems<sup>[6]</sup>.

GAs are based on Darwin's theory of sur-

vival of the fittest and implement the group search policy. Selection, crossover and mutation are the most important operators in genetic algorithms. Heuristic crossover and non-uniform mutation operators were used. The self-adaptive technique adopted is to provide the appropriate crossover and mutation probabilities. There are several techniques that can cooperate with GAs searching Pareto optimal results. In ADOP, Pareto ranking and fitness sharing technique are chosen as the key approaches, and the platform has been applied in multi-objective optimization problems<sup>[7-8]</sup>.

### 1.2 Response surface model

A response surface model (RSM) for approximation was constructed based on artificial neural network (ANN) to establish the relationship between the aerodynamic parameters of the advanced transonic stage and the design variables. It can notably reduce the computational time of 3D numerical simulation of flow field. Each design variable input into the ANN is connected to each node of adjacent layer with a series of weights, and a bias of each node is used to offset the summation of the node. The design procedure used in this paper is summarized as<sup>[9]</sup>: Firstly, sampling for the ANN. Uniform design of experiment is used to select representative samples from a large set of design variables. Secondly, train the ANN. The process of training ANN is to recalculate the weights and biases so as to minimize the overall error between the input and the desired output. After training, the RSM is also defined. The algorithm used for training the ANN is the error back-propagation algorithm. Thirdly, search the design space of RSM. Finally, validate the optimal design. The optimal result obtained from optimization of RSM is an approximate result and needed to be validated the precision of the design.

### 1.3 Uniform design of experiment

Design of experiment (DOE) is one application of mathematical statistics<sup>[10]</sup>. It is to investigate the effective method of establishing data-

base, and the main topic is how to arrange logical experiments, obtain data, and then analyze synthetically to reach optimal project. DOE plays an important role in industry production and engineering design, for example, it can increase output, improve the quality of production, shorten the period of new design, decrease cost and prolong the useful life of product. However, DOE methods demand plenty of experiments when design space is so large as to need a large number of grades of design variables. Uniform design of experiment (UDOE), as one kind of DOE methods, does well in multi-grade experiments. UDOE is an efficient method for analyzing design space, which can provide essential information with smallest quantity of samples. The main consideration of UDOE<sup>[9]</sup> is just how to uniformly distribute the most representative sample points in the design space.

## 2 3D Optimization of ATS 2 stator

ATS-2 is a transonic stage. It consists of 12 inlet guide vanes (IGVs), 14 rotors and 34 stators. At design optimization point, the rotational speed is 21 500 r/min, the mass flow is 25.26 kg/s, the total pressure ratio of stage is 2.243 3 and the adiabatic efficiency is 85.853%.

Flow in turbomachinery is highly complex and strongly three-dimensional, containing clearance leakage, boundary layer separations and shock waves, etc.. Moreover, there exist the interactions of secondary flows intensively affecting the aerodynamic performance. Therefore, three-dimensional design optimization of turbomachinery is more applicable and effective. On the other hand, design optimization of rotors, especially in transonic stage, is usually not acceptable for practice in engineering, so the improvement of stator is a feasible way.

The stator surface was changed with the trailing stacking line, performing sweep, bend and rotation. The stacking line affects significantly the three-dimensional geometrical structure and it can be easily controlled with fewer design variables. In this paper, the trailing stacking

line of the stator was controlled by a spline. As shown in Fig. 1, the section 3 is fixed, the coordinates ( and ) of section 1, 2, 4 and 5 can move in its region respectively. The stagger angles of airfoils can also be changed around stacking line in each region. Therefore, there are 12 variables together.

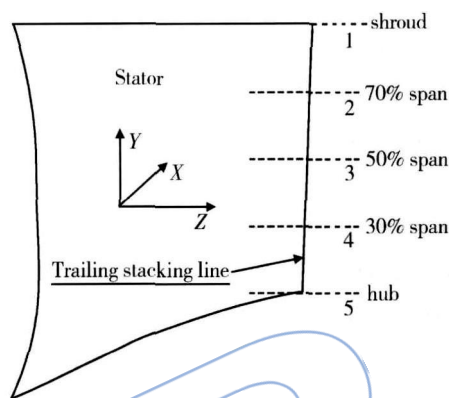


Fig. 1 Meridional view of stator

The mesh was also generated with Numeca/Igg software package, as shown in Fig. 2, consisting of  $109 \times 45 \times 49$  H-type grids at IG V,  $209 \times 21 \times 49$  O-type grids at rotor and  $109 \times 45 \times 49$  H-type grids at stator (axial, circumferential and radial directions). Thus, total number of grids is 695 751. The three dimensional flow field was solved with FINE/Turbo software package using S-A turbulence model. The inlet condition was given total pressure, total temperature and angles of velocity. The outlet condition was imposed static pressure at hub.

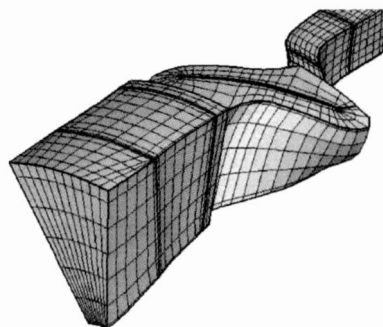


Fig. 2 Grids of ATS 2

The objective function is adiabatic efficiency, which is one of the most important aerodynamic parameters for turbomachinery.

The objective function is defined as:

$$f = \eta \quad (1)$$

where,

$$\eta^* = \frac{(\pi^*)^{\frac{k-1}{k}} - 1}{\frac{T_{ex}^*}{T_{in}^*} - 1} \tag{2}$$

$$\pi^* = \frac{p_{ex}^*}{p_{in}^*} \tag{3}$$

$\eta^*$  and  $\pi^*$  are adiabatic efficiency and total pressure ratio of stage, subscripts, in and ex indicate inlet and exit of the stage, respectively.

The optimization problem, in this paper, is single objective/single point optimization problem and the design optimization point is near stall margin with the back pressure of 180 000 Pa (hub). As a result of the optimization, the adiabatic efficiency of stage is increased by 0.502% with the mass flow increment of 0.115 kg/s at the optimal point, the adiabatic efficiency of rotor is increased by 0.183% and the total pressure recovery coefficient of stator is increased by 0.002 77, as shown in table 1.  $\eta_R^*$  is adiabatic efficiency of rotor and  $\sigma_s^*$  is total pressure recovery coefficient of stator,

$$\sigma_s^* = \frac{p_{ex}^*}{p_s^*} \tag{4}$$

and  $p_s^*$  is the inlet total pressure of stator.

Table 1 Comparison of ATS 2 aerodynamic performance

|               | Original | Optimal  | Increment |
|---------------|----------|----------|-----------|
| $\eta^* / \%$ | 85.853   | 86.355   | 0.502     |
| $\pi / \%$    | 2.243    | 2.244    | 0.001     |
| Flow / (kg/s) | 25.260   | 25.375   | 0.115     |
| $\eta_R^*$    | 89.215   | 89.398   | 0.183     |
| $\sigma_s^*$  | 0.975 03 | 0.977 80 | 0.002 77  |

Fig. 3 displays the comparison of optimal and original trailing stacking lines. It can be seen that the optimal stacking line is more complex in three-dimensional space. Fig. 4 shows the comparison of character map of original and optimal stage. The optimal stage increases the efficiency and total pressure ratio over a large scope, and especially extends the stall margin. Fig. 5 reveals that the optimal stator improves the flow near suction surface by reducing the radial deflection of streamlines. The streamlines

on suction surface of optimal stator are more flat, what are beneficial to reducing loss and enhancing stability of flow field. From Fig. 6, it can be seen that total pressure loss of optimal stage at outlet is much less than original one in tip region and basically keep the same in other regions. It can be concluded from Fig. 7 that adiabatic efficiency distribution of optimal stator is better than original one at outlet, notably in tip region. Fig. 8 is the comparison of static pressure distributions of rotors. It can be seen that there are strong shock waves on the suction surfaces of rotors and the optimal shock wave position is pushed downstream. Another improvement is that the incidence angles of stator are reduced in mid and tip regions. This can also be seen in Fig. 9 that the incidence angles of stator are obviously reduced in whole spanwise direction.

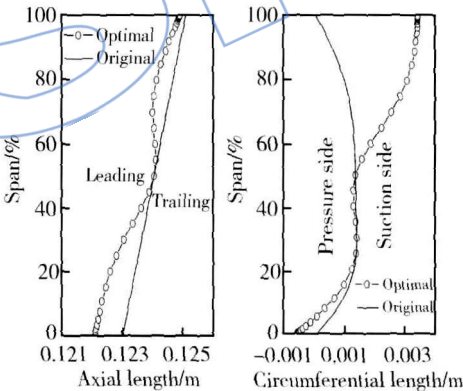


Fig. 3 Axial and circumferential view of optimal and original stacking lines of stators

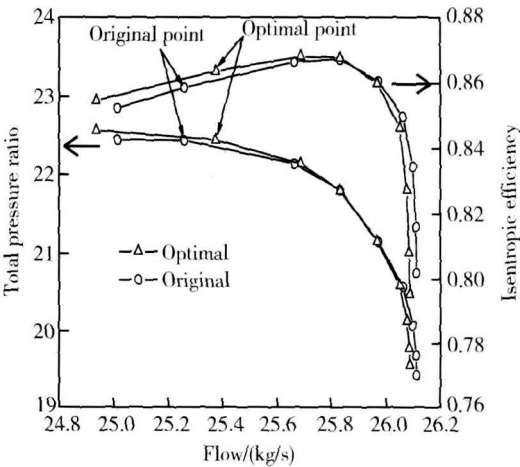


Fig.4 Comparison of character map

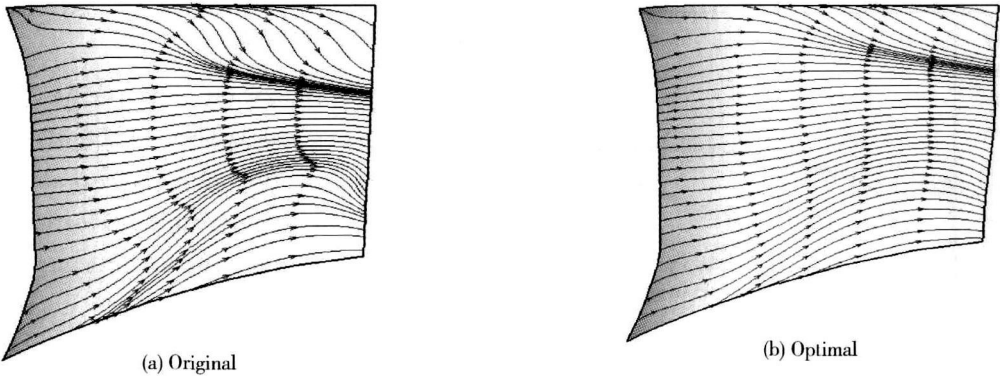
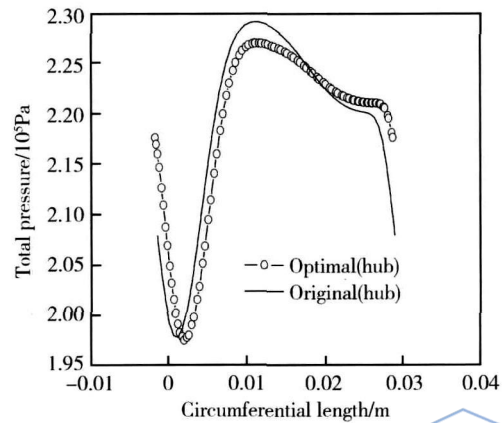
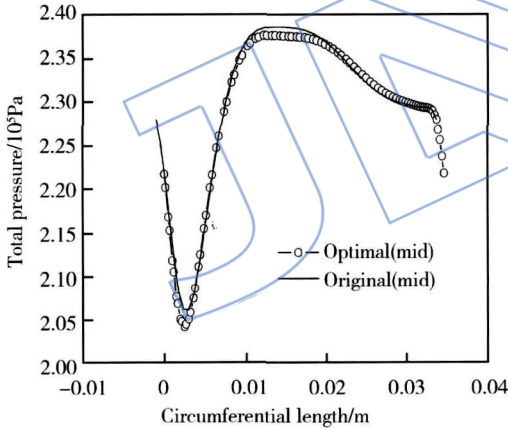


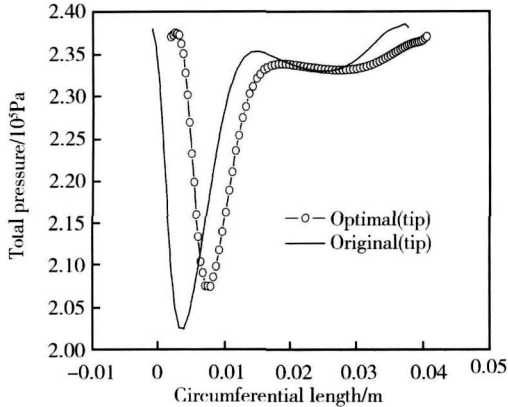
Fig. 5 Streamtraces near suction surfaces of stators



(a) 10%



(b) 50%



(c) 90%

Fig. 6 Total pressure distribution at outlet

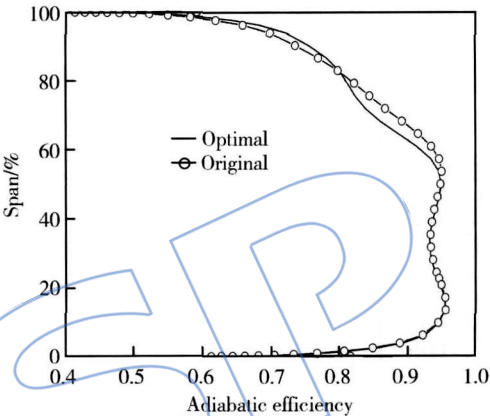
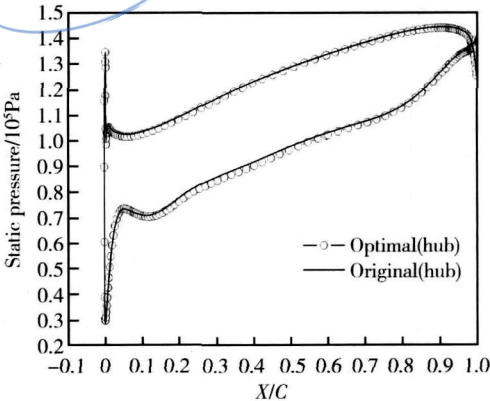
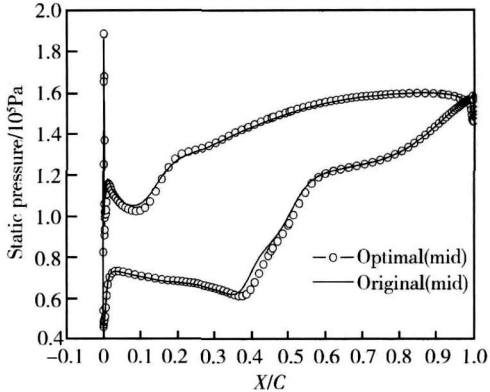


Fig. 7 Adiabatic efficiency distribution at outlet



(a) 10%



(b) 50%

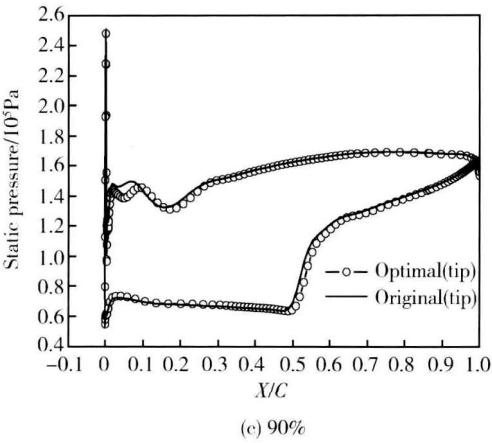


Fig. 8 Static pressure on rotor surface

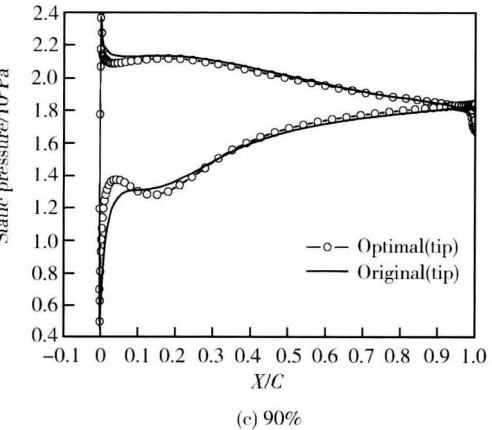
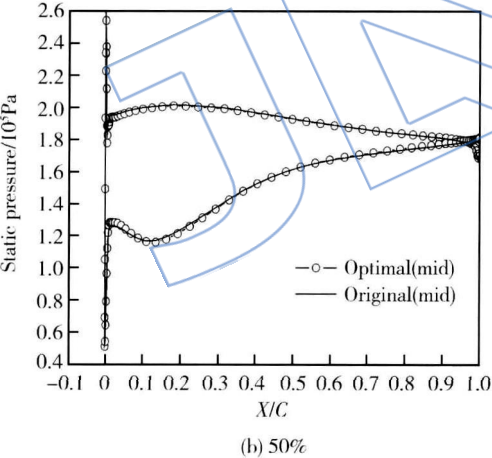
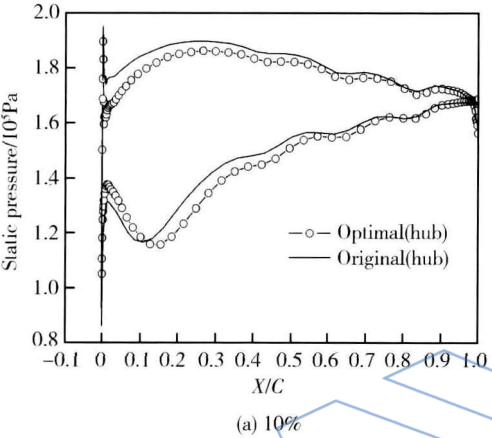


Fig. 9 Static pressure on stator surface

### 3 Conclusion

The optimization platform ADOP developed in this paper was applied in the 3D aerodynamic design optimization of ATS-2 stator significantly improves the aerodynamic performance of stage by optimizing only the trailing stacking line of stator, which will not do harm to the structure intensity.

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