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Numerical analysis and optimization of the inlet stage of a multi-stage high pressure compressor

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Abstract: An optimization process is used to redesign blades of a high pressure compressor. An artificial neural network (ANN) method is coupled to Navier Stokes solvers and is applied to three different redesigns. A new rotor blade of a transonic compressor is designed by modifying thick, stacking line and inlet angle using a 3D approach, with a significant efficiency improvement at the design point. The off design behavior of this new compressor is also checked afterwards, which shows that the whole performance of the inlet stage is improved over a wide range of mass flow. The losses are reduced, proving the good performance of the optimum. The whole results indicate that the optimization method can find improved design and can be integrated in a design procedure.

Key words: aerospace propulsion system; high pressure compressor; numerical optimization; blade row match; artificial neural network;

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Nomenclature

P	penalties
W	weight factor for objective function
Q_{imposed}	value of the imposed quantity
$Q_{\text{reference}}$	reference quantity value
Q	computed quantity value
k	exponent of the penalty term
F	objective function
IGV	inlet guide vane
R1~ R5	first rotor to the fifth rotor respectively
S1~ S5	first stator to the fifth rotor respectively
β_1, β_2	inlet and outlet metal angle of blade section
γ	setting angle of blade
η	efficiency
η_{isentro}	isentropic efficiency
π	pressure ratio
π_{design}	design value of pressure ratio
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{\text{design}}$	the design value of mass flow rate
Δ	variation before and after optimization
Z	axial coordinate
prim	intersect point of sections and stacking line

Introduction

Modern aircraft engine demands higher performance in terms of efficiency, pressure ratio or mass flow of the different components of the engine. This leads to the use of CFD in an intensive way for turbomachinery blade design but this higher performance must be achieved within shorter design cycles and at lower cost. Traditionally CFD has been used in an analysis mode for cut-and-try approaches to design, in which the design process is strongly guided by the designer expertise, with eventually a large scattering of the results. The recent progress of the CFD code performance in terms of accuracy, sensitivity and efficiency, enables to reduce the design cycle by coupling CFD codes with optimization tools. This can be applied with a Q3D or a 3D approach, with various optimization and blade parameterization techniques. There into Genetic Arithmetic is the most popular method

because of its good capability of searching global optimum, but the optimization efficiency needs to enhance.^[1-2]

This paper describes three optimization cases carried out by coupling an optimizer with ANN to Navier-Stokes solvers.

The first case concerns the efficiency improvement of a transonic compressor with an optimization method. The thick of the 1st rotor (R1) blade is modified by applying a deformation defined by a Bezier curve.

The second optimization case deals with the stacking line of the blade of R1. The centre of gravity of blade sections is chosen as stacking points, and the stacking line is parameterized by three control points Bezier line.

The third case presented concerns the inlet angle optimization of R1. The steady 3D Navier-Stokes calculation is carried out on the whole stage including IGV and the stator of the 1st stage.

The outlet metal angle and the setting angle of IGV are modified by changing the camber lines of three sections from hub to tip, in order to reform the inlet flow angle of R1. The performance of the new shape is compared with the initial at the design point as well as off design points.

1 Optimization method

The optimization strategy is composed of the following parts: The 3D Navier-Stokes analysis starts from a baseline design. According the constraint variables, the optimization algorithm produces a set of samples, which is used to build a database for ANN (artificial neural network) self-training. The optimization process is based on the ANN database. The ANN algorithm used here is coupled in a commercial software FINE™/Design 3D. Fine/Turbo is used throughout the numerical optimization of the present paper. Details is presented in references^[3-4].

2 Prototype analysis

2.1 Overall performance

A cross section of the compressor is shown

in Fig. 1. The specifications of the compressor are summarized in Table 1.

To investigate the flow field, multistage CFD were performed with a commercial CFD package FINE/Turbo. Fig. 2 shows the CFD results, the relative Mach number contour at meridian surface. Supersonic area is clearly seen in R1. Fig. 3 illustrates the compare results of stage pressure ratio and efficiency. The results show that the pressure ratio of R1 is much higher than design value, while the efficiency of R1 is much lower than design value. Higher pressure ratio makes the stage over loading, whereas the lower efficiency induces the lack in overall efficiency of multi-stage. Other stages' performance is close to the design value.

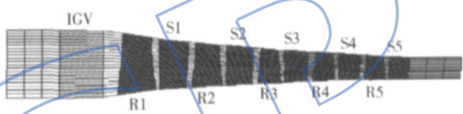


Fig. 1 Cross section of compressor

Table 1 Compressor specifications

Parameter	Value
Mass flow / (kg / s)	25
Total pressure ration	6 0
Adiabatic efficiency	0. 85
Stages amount	Axial 5

As a result we choose the 1st stage (including IGV) as the optimization object. The optimization purpose is to improve the efficiency and decrease the pressure ratio of stage 1 properly.

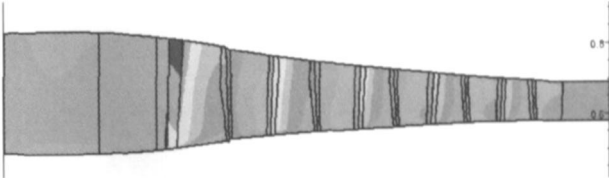


Fig. 2 Meridian relative Mach number

2.2 First Stage Performance

Fig. 4 describes the pressure ratio and efficiency of R1 span wise distribution. With the

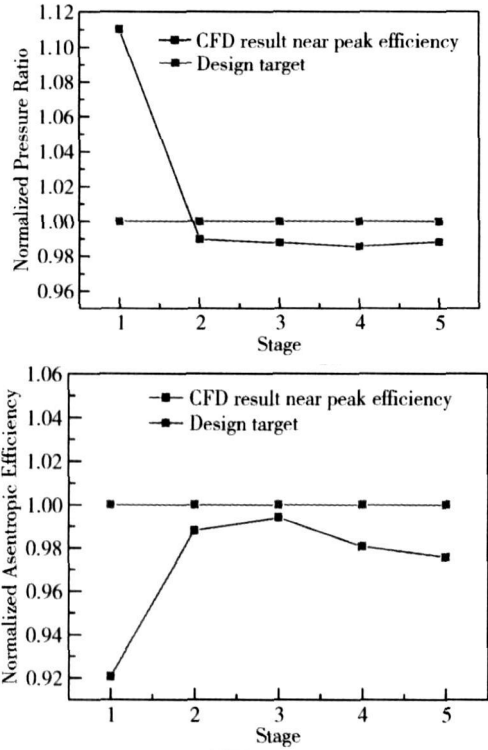


Fig. 3 Pressure ratio and efficiency of each stage

larger radius, the relative flow velocity is getting higher; hence the intensity of shock wave is higher, consequently the rotor pressure is higher. As a result, the pressure ratio near the blade tip is larger than the pressure ratio of other span places. A long with the increasing of shock wave

intensity, shock wave loss becomes the major loss of the flow, so the efficiency decreases with the radius increasing.

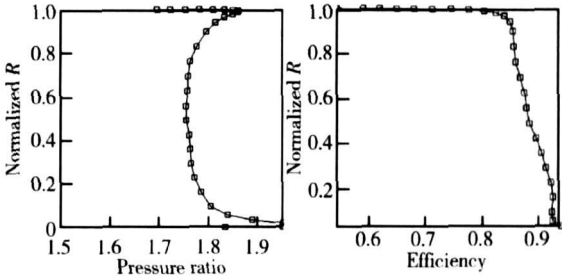


Fig. 4 R1 performance span wise distribution

Fig. 5 presents relative Mach number contour of three blade sections, which are near hub section, mid-span section, near tip section respectively. The contour illustrates that shock wave exists the whole span of R1 blade. The shock is weak near hub, but shock/boundary layer interaction brings on serious flow loss. At the mid span section and near tip section, shock wave gets stronger, but the boundary layer separation is not very large due to the supersonic profiles.

Fig. 6 presents the characteristics performance of stage one. One work state near peak efficiency was chosen as the optimization point.

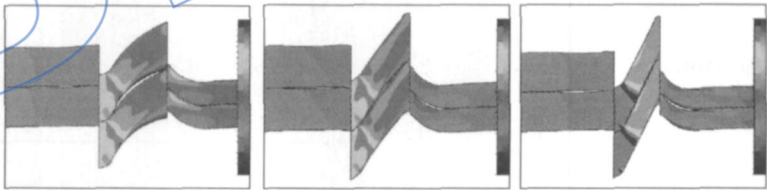


Fig. 5 Relative Mach number contour of near hub section, mid span section, near tip section of rotor blade

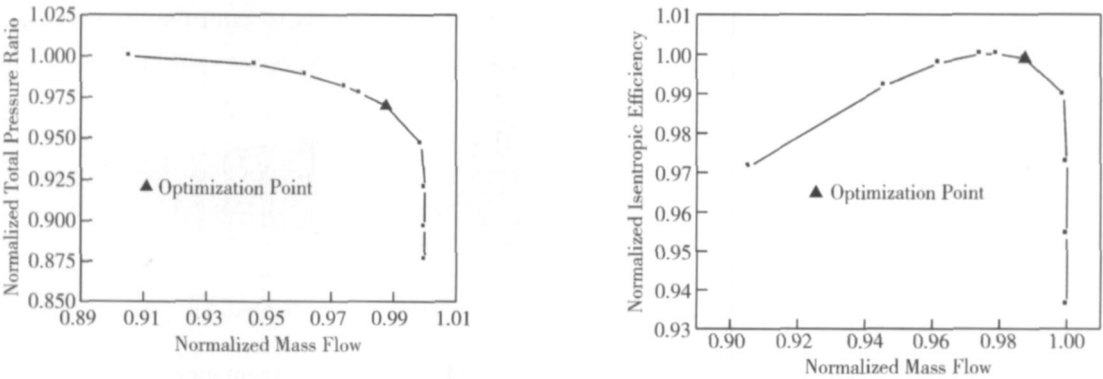


Fig. 6 Characteristics performance of first stage

3 Case 1: R1 thickness optimization

3.1 Blade parameterization

AutoBlade is used to describe a blade by a number of profile sections on the same conical surfaces that then stacked to three-dimensional blade geometry. Each profile section is defined first a camber line and added thickness distributions to obtain the suction and the pressure sides (see Fig. 7(a)(b)). The meridian trace of the stacking line is modeled by a Bezier curve with 3 control points (see Fig. 7(c)), whereas the tangential lean curve is described with a composite Bezier line-Bezier curve (see Fig. 7(d)).

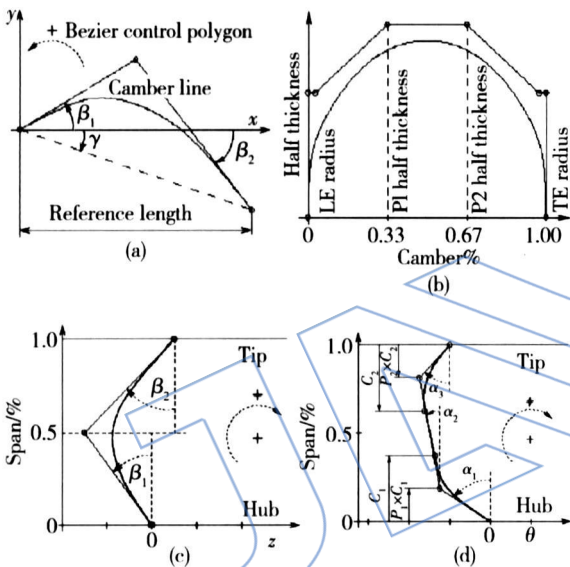


Fig. 7 Blade parameterization of R1

3.2 Constrains and objective function

In this case, the thick of three sections of R1 blade is optimized. The free geometry variables bounds are shown in Table 2.

Table 2 Free geometry variables bounds of R1 thickness

Free Geometry Variables	Min	Current	Max
S1_HALF_THICKNESS_P1	0.001	0.002141	0.0032
S1_HALF_THICKNESS_P2	0.0012	0.002576	0.0035
S2_HALF_THICKNESS_P1	0.0002	0.001001	0.002
S2_HALF_THICKNESS_P2	0.0003	0.001173	0.002
S3_HALF_THICKNESS_P1	0	0.000150	0.000650
S3_HALF_THICKNESS_P2	0	0.000226	0.000726

Three penalties are defined as following:

$\eta = 1.0$

$\pi \geq \pi_{design}$

$\dot{m} \geq \dot{m}_{design}$

According the free geometry variables bounds and the penalties, the objective is defined as formula (2).

$$P = W \cdot \left(\frac{Q_{imposed} - Q}{Q_{reference}} \right)^k \tag{1}$$

$$F(P_i) = \sum_i^n P_i \tag{2}$$

3.3 Optimization

Fig. 8 shows 50 samples composing as a database for ANN optimization. The database requires 50 calls for Navier-Stokes solver. Each computation time is about 30 minutes and the total time is about 25 hours. Observing from Fig. 8, the efficiency of the samples distributes between 0.856 and 0.879, and pressure ratio distributes from 1.608 to 1.74.

The optimization process converges in 30 iterations. The average run time for each Navier-Stokes computation is about 30 minutes on 2.4G Hz CPU. The total time of optimization is about 15 hours. Fig. 9 presents the convergence history of Objective function

The variation of the inlet stage performance is given in Table 3 below. The efficiency is notalbe increased by 1.33%. The decrease of objective function is a consequence of the efficiency, pressure ratio and mass flow increasing.

Table 3 Variation of the inlet stage performance

Performance	Improvement
Isentropic efficiency	1.33%
Total pressure ratio	0.507%
Mass flow change	1.38%

Fig. 10 gives the thickness variation before and after optimization at one section of the blade.

The relative Mach number flow field on Fig. 11 shows that the flow field structure in the duct of R1 is different: the thin blade section leads to the reduction of the relative Mach num-

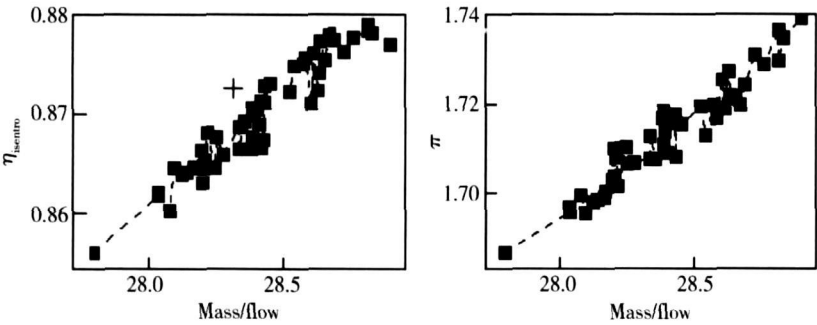


Fig. 8 Database for ANN

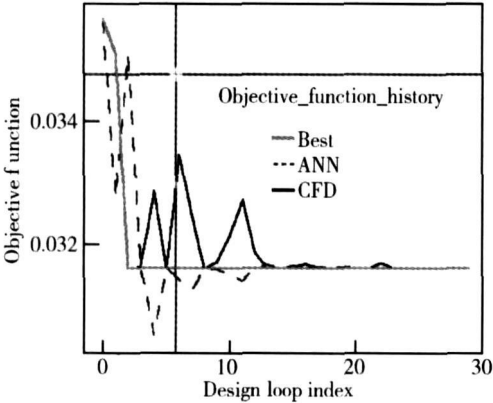


Fig. 9 Convergence history Objective function

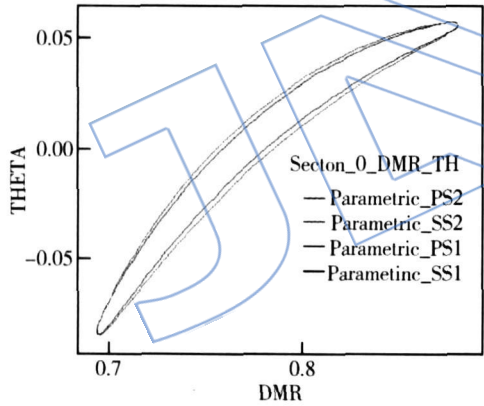


Fig. 10 Blade thickness variation before and after optimization

ber and the reduction of the separation area on the suction side of R1.

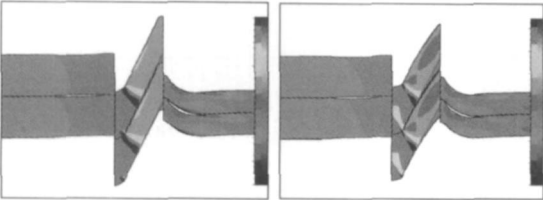


Fig. 11 Relative Mach number contours before and after optimization

The off design behavior of the blade is illus-

trated on Fig. 12. The isentropic efficiency and the normalized total to total pressure ratio are plotted as a function of the mass flow. One observes that a large part of the pressure ratio improvement at the design point is remained at off design points, whereas at off design points the efficiency is a little lower than initial design value, but the mass flow margin is greatly expended. As expected, the choking mass flow also keeps more than the design value.

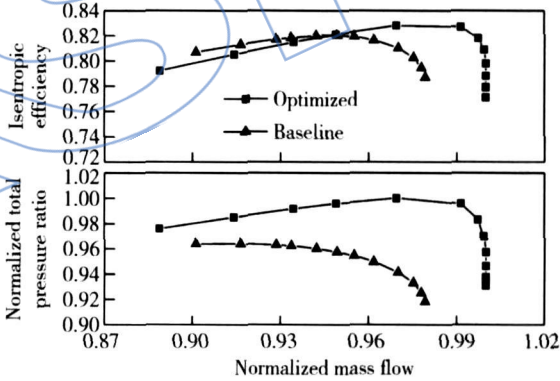


Fig. 12 Off design performance before and after optimization

4 Case 2: R1 sweep stacking line optimization

4.1 Blade parameterization

AutoBlade is used to describe a blade by a number of profile sections on the same conical surfaces that then stacked to three dimensional blade geometry. Each profile section is defined first a camber line and added thickness distributions to obtain the suction and the pressure sides. The meridian trace of the stacking line is modeled by a Bezier curve with 3 control points, whereas the tangential lean curve is described

with a composite Bezier line-Bezier curve. All of the blade parameterizations are the same as case 1.

4.2 Constrains and objective function

In this case, the optimization presented here concerns the sweep law of stacking line of R1. The objective is to improve the efficiency only by modifying the stacking law. The free geometry variables bounds are shown in Table 4.

Table 4 Free geometry variables bounds

Free Variables	Min	Current	Max
sweep_angle1	- 5.064913	- 0.064913	4.935087
sweep_angle2	- 3.499468	1.500532	6.500532
Z_stacking_sweep	0.016963	0.018963	0.020963
S1_DZ_prim	0.041019	0.043019	0.045019
S2_DZ_prim	0.033478	0.035478	0.037478
S3_DZ_prim	0.032851	0.034851	0.036851

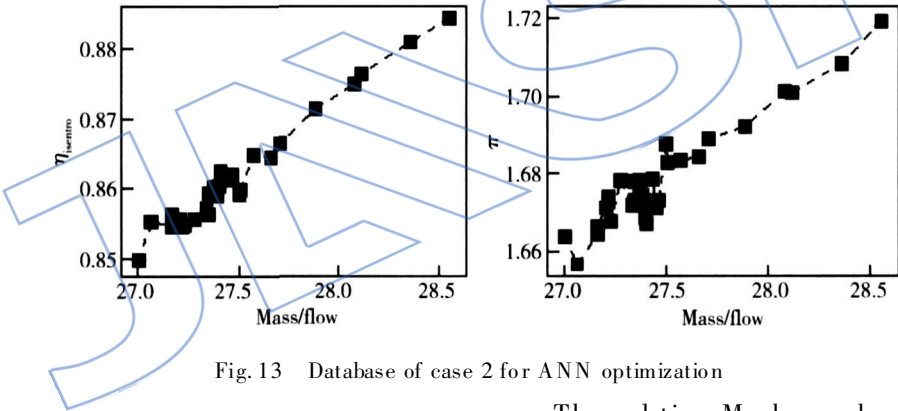


Fig. 13 Database of case 2 for ANN optimization

Table 5 Variation of the inlet stage performance

Performance	Improvement
Isentropic efficiency	1.14%
Total pressure ratio	0.45%
Mass flow change	1.04%

Fig. 14 gives the blade variation before and after optimization. The optimization results show that the sweep blade stacking line have better aerodynamic performance.



Fig. 14 Blade variation before and after optimization

The same penalties and objective functions as described in case 1 are defined in this case.

4.3 Optimization

Fig. 13 shows 30 samples composing as the database for second optimization. Seeing from Fig. 13, the efficiency of the database distributes between 0.85 and 0.885, and the pressure ratio distributes between 1.657 and 1.719. The database indicates that the efficiency of R1 could be improved by modifying the sweep law of the blade stacking line.

The optimization process converges in 30 iterations. The run time of each computation and total time is the same as case1.

The variation of the inlet stage performance is described in Table 5. The efficiency is remarkably increased by 1.14 %, and the pressure ratio and mass flow of the inlet stage rise by 0.45% and 1.04% respectively.

The relative Mach number flow field on Fig. 15 shows that the shock waves become weak after optimization, which leads to the reduction of the loss of shock waves and boundary layers.

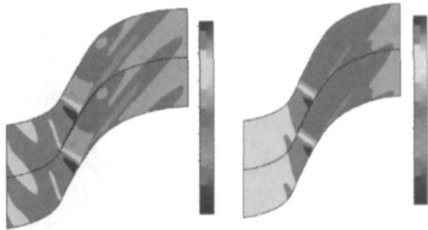


Fig. 15 Relative Mach number contours before and after optimization near blade tip of R1

The off-design behavior of the blade is illustrated on Fig. 16. The isentropic efficiency and

the normalized total to total pressure ratio are plotted as a function of the mass flow. One observes that a large part of the efficiency improvement at the design point is remained at off design points. As expected the choking mass flow is also well conserved, and the mass flow margin is greatly expended also.

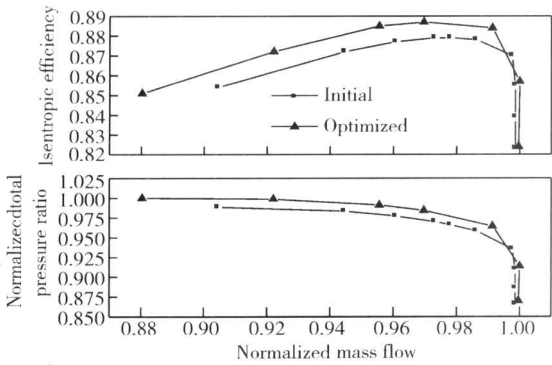


Fig. 16 Off design performance before and after optimization

5 Case 3: R1 inlet angle optimization

Fig. 17 illustrates the disordered distribution of R1 inlet flow angle along span wise. At 20% span section, the inlet incidence is positive, and the pressure distribution is forward loading. At 50% span section, the inlet incidence is more positive than that of 20% span section, and the pressure distribution is too forward loading, hence the forward after 15% chord needs increasing. At 70% span section, the pressure distribution is really chaos. This section needs to be re

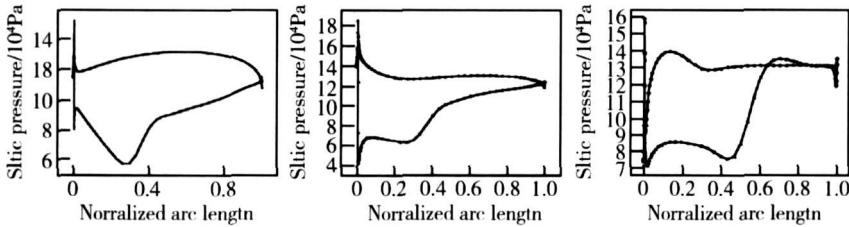


Fig. 17 Surface pressure distribution of 20%, 50%, 70% span sections, respectively

designed on 2D blade profile.

5.1 Blade parameterization

AutoBlade is also used to describe a blade by a number of profile sections on the same conical surfaces that then stacked to three dimensional blade geometry. The profile section is defined as that in case 1 (see Fig. 7(a), (b)), but the meridian trace of the stacking line is different. The sweep law of the stacking line and the tangential lean curve are both described with a composite Bezier line Bezier curve (see Fig. 18 (a), (b)).

5.2 Constrains and objective function

In this case, the setting angles and the outlet metal angles of three sections of IGV blade are optimized to reform the inlet flow angle of R1. The free geometry variables bounds are shown in Table 6.

Table 6 Free geometry variables bounds of IGV

Free Variables	Min	Current	Max
S1_CAMBER_GAMMA	-20	0.359352104013135	2
S1_CAMBER_BETA2	-20	1.42561671098677	2
S2_CAMBER_GAMMA	-20	1.49676870817163	2
S2_CAMBER_BETA2	-20	5.93712906981511	6
S3_CAMBER_GAMMA	-20	-1.285707467641	5
S3_CAMBER_BETA2	-35	-14.4929123964746	-5

The penalties are defined the same as that in case one.

According the free geometry variables bounds and the penalties, the objective is defined as formula (2).

The CFD calculation in this case is carried out on three rows of the inlet stage (See Fig. 19). The grid is made up of 3 blocks (H topology) in the main duct. The node distribution in

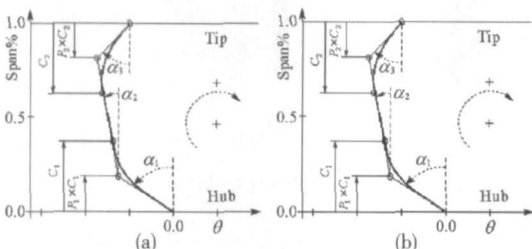


Fig. 18 Blade parameterization of IGV

the different blocks is given in Table 7 below and the total node number is 443223.

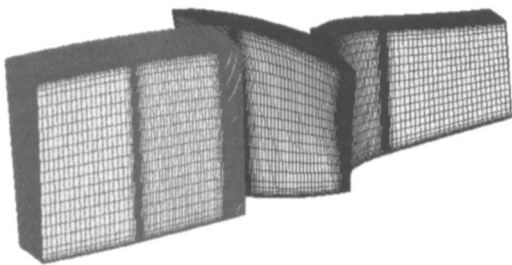


Fig. 19 Mesh topology of optimization 3

Table 7 3D grid characteristics

	IGV	R1	S1	Total
Tangential	33	37	133	137973
Span wise	33	37	121	147741
Axial wise	33	37	129	157509

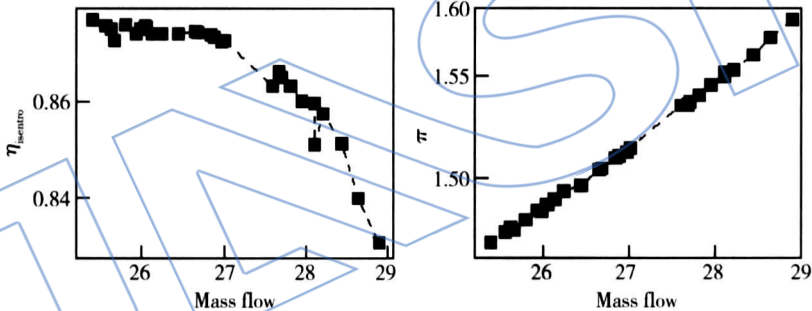


Fig. 20 Database of case 3 for ANN optimization

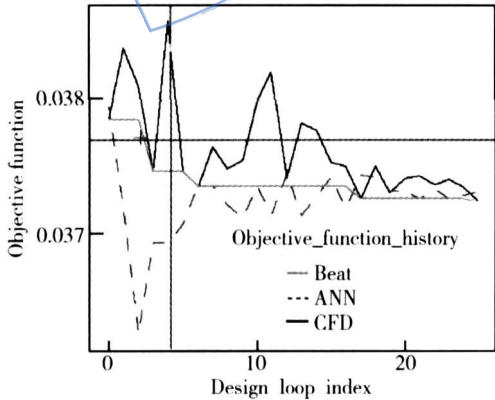


Fig. 21 Convergence history of objective function

efficiency librates during the whole iterate process.

In this steps, because the control variables β_1 , β_2 , γ of IGV are defined by the angle between

5.3 Optimization

Fig. 20 describes the database containing 30 samples for ANN optimization. We can clearly see from the efficiency reduces as the mass flow increasing; contritely the pressure ratio rises as the mass flow increasing. The maximum and the minimum efficiency are respectively 0. 831 and 0. 878. The maximum and the minimum pressure ratio is 1. 42 and 1. 59.

The optimization process converges in 28 iterations. The average run time of each Navier-Stokes computation is about one and a half hours on PC with 2. 4G Hz CPU. The total optimizing time is about 40 hours. Fig. 21 presents the convergence history of Objective function. The objective function descends obviously, but the the control points direction and the axial direction, during the optimization process the free

variations of β_2 , γ are not suitable for R1. In this condition, we adjust the β_2 , γ on the basis of the optimization result. The variation of the inlet stage performance is described in Table 8, the efficiency and pressure ratio are remarkably increased by 4. 55% and 10. 72% respectively. The mass flow descends a little but still above the design value.

Table 8 Variation of the inlet stage performance before and after optimization

Performance	Improvement
Isentropic efficiency	4. 55%
Total pressure ratio	5. 09%
Mass flow change	- 2. 07%

The meridian relative Mach number contours before flow field on Fig. 22 describes that the shock wave structure near blade tip of R1 reforms and leans into the duct of R1. Fig. 23 shows the relative Mach number contours on Blade-to-Blade surface before and after optimization. We can clearly see that before optimization the shock wave is normal to the blade suction, which induces large boundary separation area, but after optimization the shock leans afterward, and the boundary layer becomes invisible on Fig. 23.

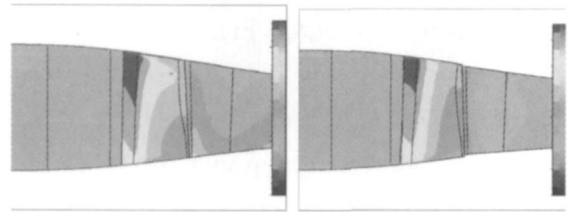


Fig. 22 Meridian relative Mach number contours before and after optimization

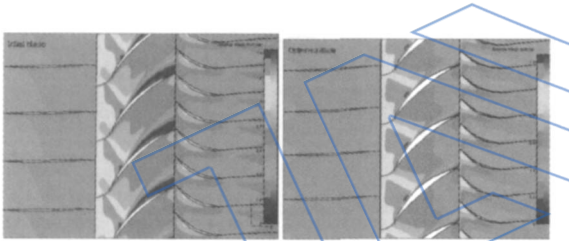


Fig. 23 Relative Mach number contours on B-B surface before and after optimization

The off-design behavior of the optimized blade is illustrated on Fig. 24. The isentropic efficiency and the normalized total-to-total pressure ratio are plotted as a function of the mass flow. One observes that large parts of the efficiency and pressure ratio improvement at the design point are remained at off design points. But the mass flow margin is reduced.

6 Conclusion

The paper presents an optimization process on the inlet stage of a multistage compressor by using a commercial optimizer Design3D. The optimization is carried out through 3 steps. The first step of optimization is focused on the thickness of the 1st rotor blade sections. The second

step concerns the sweep law of the 1st rotor

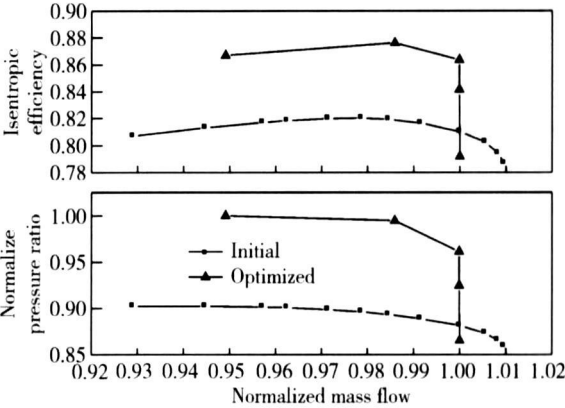


Fig. 24 Off design performance before and after optimization

stacking line. The third step pays attention to the interaction of rotors and stators, and optimizes the inlet flow angle through modifying the outlet metal angle of the IGV. Though the three steps of optimization, the structure of the flow field in the inlet stage reformed, simultaneously the shock wave is adjusted to reduce the shock/boundary layer separation area, hence the loss is decreased. The new blade has its efficiency increased by 5.6 %, and its pressure ratio increased by 5.09%, while the mass flow has a little descends by 2.07%. Moreover the off design performance of inlet stage is checked, the results shows that the improvements at design point are remained at off designed point.

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