# Study on Aerodynamic Optimization Design Process of Multistage Axial Turbine

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## Abstract

An aerodynamic optimization design process of multistage axial turbine is presented in this article: first, applying quasi-three dimensional (Q3D) design methods to conduct preliminary design and then adopting modern optimization design methods to implement multistage local optimization. Quasi-three dimensional (Q3D) design methods, which mainly refer to S2 flow surface direct problem calculation, adopt the S2 flow surface direct problem calculation program of Harbin Institute of Technology. Multistage local optimization adopts the software of Numeca/Design3D, which jointly adopts genetic algorithm and artificial neural network. The major principle of the methodology is that the successive design evaluation is performed by using an artificial neural network instead of a flow solver and the genetic algorithms may be used in an efficient way. Flow computation applies three-dimensional viscosity Navier–Stokes (N-S) equation solver. Such optimization process has three features: (i) local optimization based on aerodynamic performance of every cascade; (ii) several times of optimizations being performed to every cascade; and (iii) alternate use of coarse grid and fine grid. Such process was applied to optimize a three-stage axial turbine. During the optimization, blade shape and meridional channel were respectively optimized. Through optimization, the total efficiency increased 1.3% and total power increased 2.4% while total flow rate only slightly changed. Therefore, the total performance was improved and the design objective was achieved. The preliminary design makes use of quasi-three dimensional (Q3D) design methods to achieve most reasonable parameter distribution so as to preliminarily enhance total performance. Then total performance will be further improved by adopting multistage local optimization design. Thus the design objective will be successfully achieved without huge expenditure of manpower and calculation time. Therefore, such optimization design process may be efficiently applied to the aerodynamic design optimization of multistage axial turbine.

## Introduction

With the continuous progress of design technology of turbomachinery, the requirements on the theory of blade profiling and design method are much higher than before. The blade design always decides many performance parameters, such as efficiency, pressure ratio, weight and so on. Aerodynamic design plays a core role in design of turbomachinery since no high level performance can be achieved without high level aerodynamic design. With the rapid development of numerical simulation study of cascade flow field with Wu's theory[1)] as main thread in the whole world in 1960s and 1970s, quasi-three dimensional (Q3D) design system is established by applying radial equilibrium equation and internal flow computation of two-dimensional (2D) cascade. Such Q3D design method was widely adopted in the past.

In recent years, a large mount of optimization design is adopted to improve the performance of turbomachinery. Toyotaka et al.[2)] applied a multidisciplinary optimization procedure to decrease shock loss of 2D transonic turbine blade. Optimization method was evolution strategy (ES) and a Q3D N-S solver HSTAR with a low-Re k-ε turbulence model has been used to flow simulation. Lenid et al.[3)] firstly redesigned a vane by an inverse design method with applying AxSTREAMTM software and analyzing 3D flow field with CFX-5.7. Then they simply discussed multidisciplinary 3D optimization problem. Optimization utilized the design of numerical experiment (DOE) technique. However, no detail method and example were presented. Kammerer et al.[4)] optimized a 1.5-stage turbine and the design sensitivities used within the optimization are obtained by numerically solving the analytical sensitivity equations. 3D N-S flow solver ITSM3D was applied to analyze flow field and blade is parameterize with B-spline curve. Andrea et al.[5)] redesigned an 3D high-lift turbine cascade by means of CFD analyses and optimization techniques. Blade geometry was handled in a fully 3D way, using Bezier curves and surfaces for both camber–surface and thickness distribution. The fluid solver applied steady 3D N-S solver TRAF. The optimization procedure different techniques were adopted: a GA strategy made it possible to considerably reduce 2D profile losses, while the optimal stacking line was found based on a successive DOE analysis. Martina et al.[6] applied an ES with covariance matrix adaptation (CMA) to design an ultra-low aspect ratio transonic turbine stator blade in order to seek a new aerodynamic design concept for lower secondary flow losses. Blade parametrization utilized non-uniform rational B-spline (NURBS) and the simulation of the fluid dynamic properties we used 3D N-S flow solver HSTAR3D. Through optimization design, an extreme-aft loaded blade was obtained.

However, few articles can be found at present in relation to the study of combining modern optimization design methods and Q3D design methods to design turbomachinery. An aerodynamic optimization design process of multistage axial turbine is presented in this article: first, applying Q3D design methods, which mainly refer to S2 flow surface direct problem calculation, to conduct preliminary design and then adopting modern optimization design methods to implement multistage local optimization. Moreover, such methods are applied to optimize a 3-stage axial turbine herein.

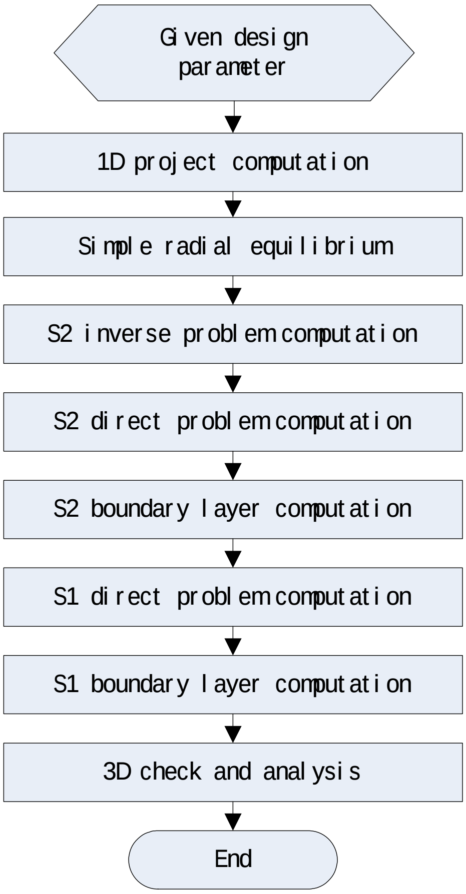


Fig.1 Schematic diagram of traditional aerodynamic design process

**Design process**

Figure 1 is the schematic diagram of traditional aerodynamic design system of turbine. Since this design is a remodel design and it has original model as initial parameters, S2 flow surface direct calculation (adopting the S2 flow surface direct calculation program of Harbin Institute of Technology[7])is directly conducted from the original parameters, then selecting blade model according to the original blade. The preliminary design adopts Q3D design so as to make the parameter distribution most reasonable. This process does not need too much manpower and the total performance will improve in some degree. However, if continue to apply Q3D method to improve performance, a great deal of manpower is required and it is very difficult to achieve the proposed design aim, therefore, modern design method shall be adopted to continue the design. Though less manpower is required by adopting optimization method, for multistage turbine, about a hundred variables are required for each cascade, thus several hundreds of variables are required, therefore huge sample database space is required if directly optimization is conducted and as a result, the optimization can not be efficiently performed. As a solution, the improvement of the total performance may be achieved by improving local performance through applying local optimization methods, which will be set forth in detail in following section. Figure 2 is the schematic diagram of the combined design process of Q3D and multistage optimization.

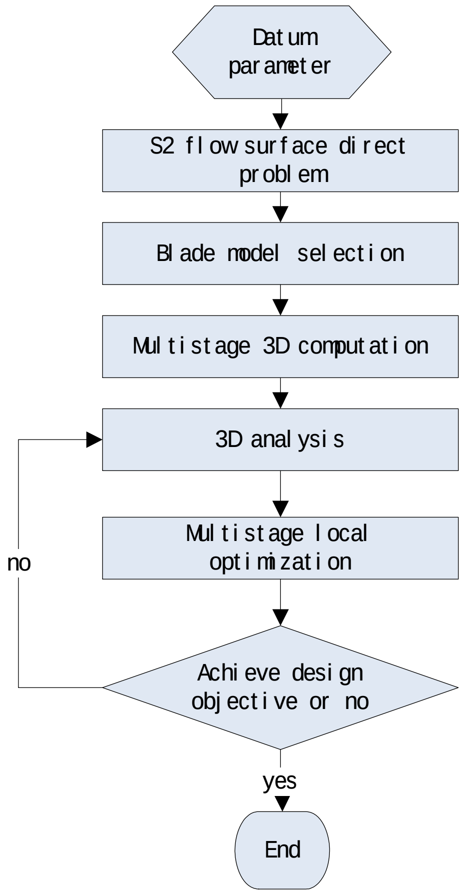


Fig.2 Schematic diagram of the combined design process of Q3D and multistage optimization

## Local optimization design

### Parametric blade

The hub and shroud in every cascade are respectively indicated in polyline with 20 variables. The stators and rotors are stacking with 7 sections (from hub to tip is from section 1 to section 7). Each section is constructed by independent suction side and pressure side, which are defined by Bezier curve. Four control points are distributed on the pressure side and five control points are contributed on the suction side. The blade shape of each section is controlled by above-mentioned nine control points, leading radius control point, trailing radius control point and wedge angle control point. Every control point is indicated in its relative situation to the camber line, which is defined by second order Bezier curve through stagger angle, inlet geometry angle and outlet geometry angle. Therefore, every section has 15 independent variables and 7 sections have 105 independent variables. In relation to space stacking mode, the stator adopts leading stacking and the rotor adopts gravity stacking so as to satisfy the intensity requirements. The tangential and meridional stacking laws are described with a composite Bezier-line-Bezier curve. There are 7 tangential and 15 meridional independent variables.. Therefore, there are 127 independent variables in every cascade if hub and shroud are not changed while 167 independent variables if hub and shroud are changed.

### Optimization methods

The usual optimization methods include: GA, SA and based on gradient method etc., of which GA and based on gradient method are the broadest used methods. It is well known that optimization methods based on gradients techniques are efficient in terms of convergence rate, but do not guarantee to produce the global optimum[8)]. On the other hand, GA offers the advantage of enhancing the probability of reaching the global optimum, but may require thousands of iterations[9)], so directly coupling with a 3D N–S solver will cause too much computation, therefore such method shall not be directly adopted and it shall be applied with other method. In this article, the software of FINE/Design3D[10)] is adopted, which jointly adopts GA and ANN. Its major principle of the methodology is that the evaluation of the successive designs is performed using an ANN instead of a flow solver, which permits to use the GA in an efficient way[11)].

### Optimization process

Every cascade has 167 independent variables, and even if the stacking laws and are not changed, every cascade still has 145 independent variables. Thus, if optimization design is directly executed, sample databases space will be very gigantic so that optimization cannot nearly accomplish due to both long computation time and poor calculation capability. Therefore, adopting 3D local optimization only to locally optimize one cascade in every time, sample databases space will be greatly diminished and optimization will favorably and efficiently be executed.

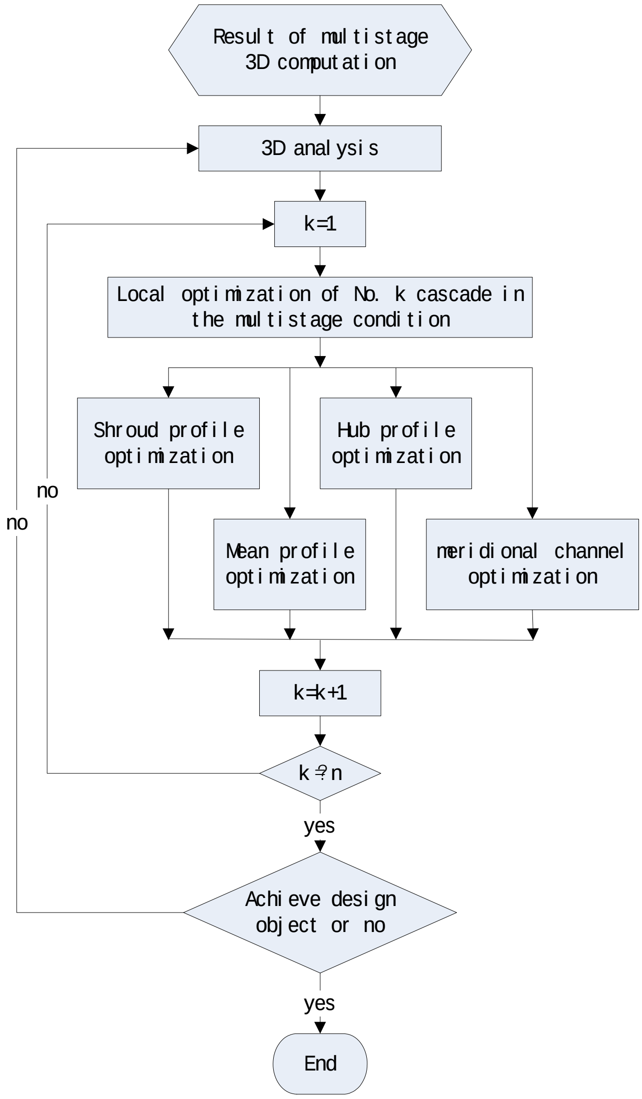


Fig.3 Schematic diagram of multistage local optimization design process

Figure 3 is the schematic diagram of multistage local design optimization process. Firstly, multistage 3D calculation and 3D analysis are applied to the result of Q3D design. Then, according to the result of 3D analysis, every cascade is locally optimized in multistage environment one by one. After the optimization of every cascade is completed, the first round optimization design is accomplished. If the design objective is achieved, optimization design is ended. Otherwise, the result of the first round design is calculated and analyzed, and the second round local optimization design is executed based on the analytic result. Thus repetition, the optimization design is not stop until the design objective is achieved. To every cascade, based on the analytic result, there may be big loss in its hub, mean or tip. When optimizing the cascade, the optimization may be conducted separately on the hub profile, mean profile, tip profile or the meridional channel, or on the combination of any of them so as to reduce the optimization time and enhance the optimization efficiency. For decreasing design time, 3D flow computation is firstly calculated with coarse grid and then is checked by adopting fine grid. During the optimization design, penalty function method is adopted to achieve the optimum efficiency, namely to maximize the efficiency, and to control the flow mass almost invariability.

Table.1Collection of Different Work Conditions

| relative speed | relative mass flow $m/m_0$ |
|---|---|
| $n/n_0$=1.00 | 1.00 0.83 0.59 0.53 |
| $n/n_0$=0.75 | 0.71 0.50 0.41 |

### Fluid numerical simulation

Steady state 3D viscosity N–S equation calculation was carried out herein. The reliability of computation was verified through numerical simulating the internal flow in a 4-stage axial test turbine at different work conditions (different mass flow and rotation speed). The 4-stage axial turbine rig is a low speed air test turbine, which was set up by Hanover University of Germany. The design condition is rotational speed n0 =7500rpm, mass flow m0=7.8kg/s and so on. Table 1 is the collection of numerically simulated different work conditions (refer to 12) for detail). Numerical computation was respectively implemented with 3 different set of grids under such work conditions. Table 2 is the collection of calculation grids.

Table.2 Collection of Calculation Grids

| | Inlet | Cascade 1-8 | outlet | Sum up: |
|---|---|---|---|---|
| | H type | O type | H type | |
| Grid1 (1.1) | 33□33□17 | 21□33□169 | 41□33□17 | 1,029,530 |
| Grid2 (1.8) | 33□49□17 | 25□49□169 | 41□49□17 | 1,809,186 |
| Grid3 (2.4) | 33×65×17 | 25×65×169 | 41×65×17 | 2,370,714 |

Figure 4 is the comparative figure between test and computation for turbine internal efficiency. In the figure, legend '7500_exp' denotes the test result as n/n0=1.00, legend '7500_2.4' denotes the computation result with grid3 (the total number of grid points is about 2,400,000 ) as n/n0=1.00, legend '5625_exp' denotes the test result as n/n0=0.75, legend '5625_2.4' denotes the computation result with grid3 (the total number of grid points is about 2,400,000 ) as n/n0=0.75 and the others are similar. The efficiency is internal efficiency. From figure 4, it is found that the total performance of numerical results show good agreement in tendency with experiment data. Hence the numerical simulation software can be recognized to be able to effectively simulate flow field.

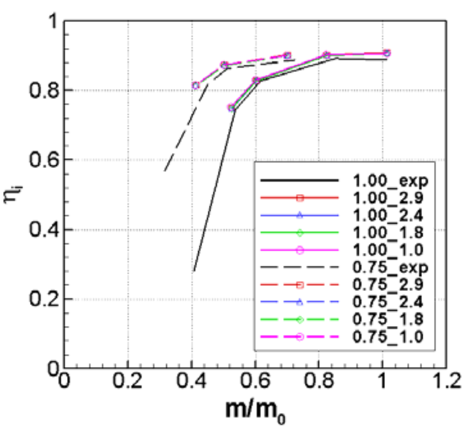


Fig.4. Turbine overall performance.
mass flow—internal efficiency

### Example and result

Such optimization design process is applied to optimize a 3-stage axial turbine. The design objective of this turbine is that efficiency increases up 1% and power capability does not decrease at the same time mass flow rate only has slight change, i.e. the change of mass flow rate does not exceed 1%.

### Numerical computation

Steady state 3D viscosity N–S calculation was carried out with Spalart-Allmaras turbulence model and the 2nd order upwind spatial discretization. On the inflow boundary condition, total pressure, total temperature and axial intake is given. On the outflow boundary condition, static pressure is specified. No-slip boundary condition is given to solid wall. Computation grid adopted H-O-H-topology grid, i.e. inlet segment and outlet segment adopted H-topology and stator zone and rotor zone adopted O-topology. Figure 5 is the schematic diagram of the 1st stage grid. Table 3 is the grid gather of optimization calculation grid and check calculation grid.

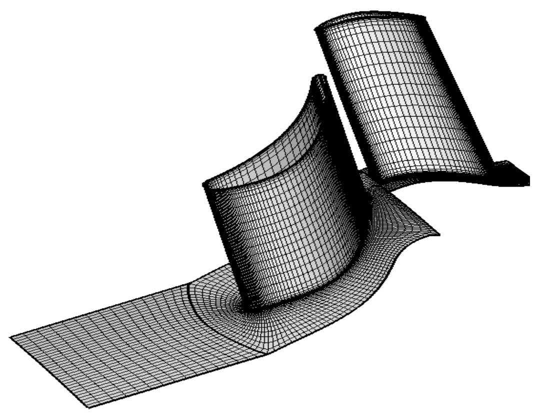

Fig.5 Schematic diagram of the 1st stage grid

Table.3 Calculation grid

| | Grid type | Optimization grid | Check grid |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Inlet | H | 33□33□17 | 41□65□21 |
| Cascade 1-6 | O | 21□33□173 | 33□65□273 |
| Outlet | H | 45□33□17 | 73□65□17 |
| Sum up: | | 763,092 | 3,650,140 |

**Local optimization process**

Taking example for the forth cascade (rotor of the second stage) illustrates how to conduct local optimization in multistage environment (the meridional channel and stacking line are changed in the optimization process). Figure 6 is the surface static pressure distribution of the 4th cascade hub (about 5% blade height). The surface static pressure is relative surface static pressure. Figure 7 is the energy loss coefficient distribution of the 4th cascade. In the two figures, legend 'ori' denotes the datum result and legend 'opt' denotes the optimization retrofit result.

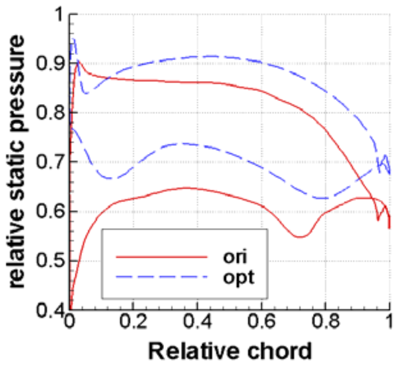


Fig.6 Surface static pressure distribution of the 4th cascade hub

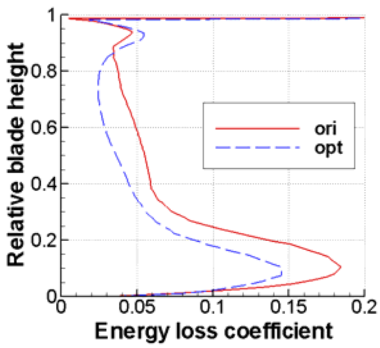


Fig.7 Energy loss coefficient distribution of the 4th cascade

From figure 6, it is found that the result of datum has bigger positive incidence so that incidence loss is bigger here, i.e. cascade match is bad here. In the fore part of cascade, cross pressure gradient is bigger and burden is bigger so as to have bigger secondary flow loss, and there is an inverse pressure segment and bigger inverse pressure gradient in suction side for datum so as to have bigger profile loss. In the rear part of cascade, it is the same as the front part, namely has bigger profile loss and secondary flow loss. Above analysis is uniform to the energy loss coefficient distribution on figure 7. Local optimization is respectively executed to each part aiming at above analysis. Firstly, changing the inlet geometry angle and stagger angle in section 1, 2 and 3 (sum up $2 \times 3 = 6$ variables) to optimize cascade match. Secondly, adjusting the fore 2 control points in suction side and pressure side in these 3 sections (sum up $2 \times 2 \times 3 = 12$ variables) to reduce the profile loss and secondary flow loss in the fore part of cascade. Finally, changing the rear 2 control points in suction side and pressure side in these 3 sections (sum up $2 \times 2 \times 3 = 12$ variables) to decrease the profile loss and secondary flow loss in the rear part of cascade. Thus each time local optimization only changed smaller variables so that the sample database space was not very gigantic. Hence, optimization design may be rapidly and effectively executed.

From figure 6, it is found that incidence loss, profile loss and secondary flow loss all diminished after optimization design and it is uniform to the energy loss coefficient distribution on figure 7. For cascade mean and cascade tip, the same analysis and local optimization methods are adopted as the cascade hub.

Table.4 Total performance collection

| | Datum | Redesign |
|---|---|---|
| Isentropic efficiency (%) | 92.9 | 94.2 |
| Mass flow rate (kg/s) | 19.38 | 19.49 |
| Power (MW) | 9.05 | 9.27 |

**Total result**

Table 4 is the total performance collection of datum and retrofit. The efficiency is isentropic efficiency. Some results can be found that: total efficiency enhanced from 92.9% to 94.2% and the improved 1.3%; total flow rate changed from 19.38kg/s to 19.49kg/s and changed 0.6% thus only a small change; total power increased from 9.05MW to 9.27MW and increased 2.4%. Therefore, the total performance is improved and the design objective is achieved.

## Conclusions

In this article, a multi-objective aerodynamic optimization design process of multistage axial turbine is presented and it is applied to optimize a 3-stage axial turbine. Some conclusions are gained as follows:

(1).The preliminary design adopts Q3D design so as to make the parameter distribution most reasonable to preliminarily enhance total performance. Then multistage local optimization design is adopted to continue to improve performance. Thus design objective is achieved in conditions that no mass manpower and time are cost. Therefore, such optimization design process may be efficiently applied to the aerodynamic design optimization of multistage axial turbine.

(2).During optimization design, 3D flow computation is firstly calculated with coarse grid then is checked with fine grid. Thus not only the design objective can be ensured, but also the design time greatly decreases and optimization design efficiency is enhanced.

(3).During optimization, local optimization based on the aerodynamic performance of every cascade can reduce sample database space. Thus the problem that directly multistage optimization design cannot be executed due to very gigantic sample database space can be solved.

(4).During optimization, several optimizations being performed to every cascade can reduce the variables of every optimization computation. Thus the size of sample database space can be easy to limit in a little scale so as to high efficiently implement optimization.

(5).Through optimization design, the performance of every cascade is improved and the parameter match between every cascade is enhanced. As a result, total efficiency increased 1.3%, and flow mass rate only slightly changed, and total power increased 2.4%.

In this article, optimization design is performed in single operating condition. In future work, multistage aerodynamic optimization design in multi operating condition can be study. Furthermore, though the total efficiency of this turbine is improved 1.3% by present optimization design, it still has enhancement space, so optimization design may continue to be executed.

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