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Turbine Blade Aerodynamic Optimization Based on Variable Dimensionality Model

Liangbo AO[1, a], Yuansheng LI[1, b], Lei LI[1, c], Zhixun Wen[1, d], Zhufeng YUE[1, e]

[1]Department of Engineering Mechanics, Norwestern Polytechnincal University, Xi'an 710129, P. R. China

[a]aolb@yahoo.cn, [b]liyuansheng@mail.nwpu.edu.cn, [c]lilei2005@yahoo.cn, [d]zxwen@nwpu.edu.cn, [e]zfyue@nwpu.edu.cn

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Abstract. The aerodynamic optimization for turbocharger turbine blade is studied using variable dimensionality analysis technology. The aerodynamic optimization procedure is decomposed to two steps: two-dimensional (2D) optimization and three-dimensional (3D) optimization based on the 2D optimal results. The quintic polynomial method with continuous three order derivatives is used to present section profile of three sections, root, middle and tip of blade. The 2D aerodynamic analysis and optimization are carried separately for different sections. Aerodynamic optimization for turbine blade is driven by the combination of global and local optimization arithmetic, with the 2D optimization blade as initial value, and profile parameter as design variable. The result shows that the calculation time is shortened and the optimization efficiency is improved, compared with the full 3D optimization under the same effect.

Introduction

In the traditional method of aerodynamic design for blade, the analysis on calculation results of initial flow field has been taken first, and the design parameters of profile has been modified according to experience until the satisfactory profile has been obtained. This caused long design period and huge workload [1]. Based on the traditional method, 3D aerodynamic optimization method reduces the working strength of the designers by the automated optimization of blade aerodynamic optimization [2], but it also takes the biggish calculation cost.

In recent years, the variable complexity optimization (VCO) has been one important part of multidisplinary design optimization (MDO) because it can lower the calculation complexity of simulation optimization efficiently [3]. The main idea is that we can use the high complex model and the low complex model at the same time during optimization process. The optimization accuracy can be improved by high complex model. The calculation cost can be reduced by using low complex models. As one of the VCO, the variable dimension optimization (VDO) is applied in aerodynamic optimization of turbine blade in this paper.

Plane cascade design

Using the five-order polynomial expression proposed by Feng [4], the turbine blade profile is obtained as shown in Fig. 1. The plane cascade profile is made up of four parts, leading edge, trailing edge, pressure side and suction side. The third derivatives at the joints must be continuous. The control parameters of blade profile include: blade number (N), section location (R), blade length (S), chord length (b), radius of leading edge (R_q), radius of trailing edge (R_h), angle of attack (i), structural angle of leading edge (β_q), structural angle of trailing edge (β_h), inlet angle of air (β_1), outlet angle of air (β_2), setting angle (γ), wedge of leading edge at inlet (φ_1), wedge of trailing edge at outlet (φ_2) and deviation angle (δ).

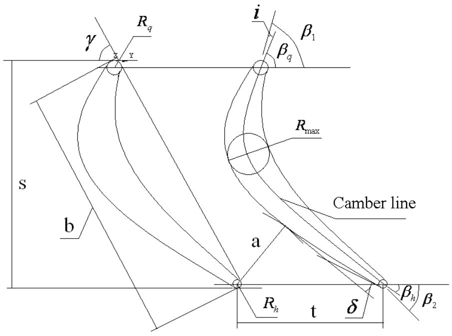


Fig. 1 Turbine blade profile

The rapid development of computational fluid dynamics (CFD), especially three-dimensional CFD, makes the simulation results of blade more really. But plane cascade still plays an important role in the whole design process, because of the low research cost and easy measurement [5]. The flow through the cascade reflects the around flow characteristics and loss feature of a basic-element cascade passage. In this paper, the loss feature of cascade is studied.

There are four main kinds of losses of turbine cascade: friction loss of profile, trailing edge loss, loss of shock wave and mixing loss between cool air and main current. The general coefficients of cascade loss are: energy losses coefficient, efficiency of cascades, velocity coefficient, total pressure recovery coefficient and total pressure loss coefficient. The coefficient of total pressure loss is defined as the ratio of the difference between total pressure of cascade inlet and outlet to the difference between total pressure and static pressure of cascade outlet, followed as:

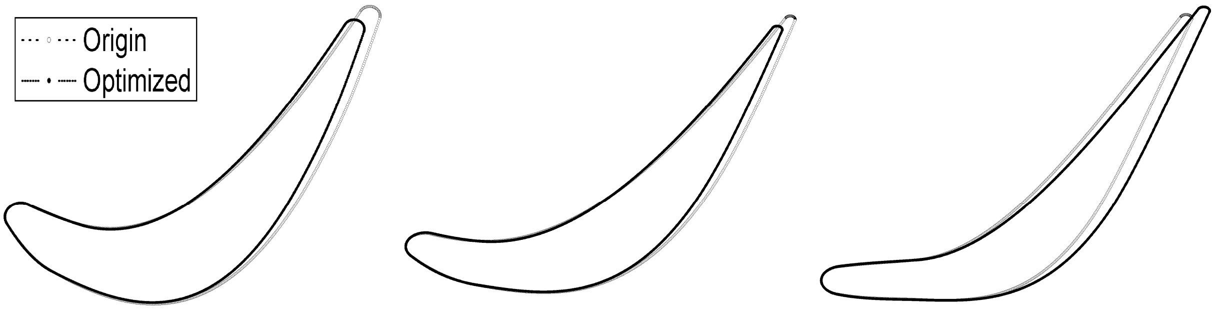
$$Y = (P_{ti} - P_{to}) / (P_{to} - P_{so}) \quad (1)$$

Where P_{ti} is the total pressure of cascade inlet, P_{to} is the total pressure of cascade outlet, P_{so} is the static pressure of cascade outlet.

In order to obtain cascade profile with good aerodynamic performance, three section profiles of turbine blade (root, middle, and tip) have been designed. The 2D optimization of the three profiles has been taken, with the chord length, the radius of leading edge, the radius of trailing edge, the angle of attack, the setting angle, the wedge of leading edge at inlet, the wedge of trailing edge at outlet and the deviation angle as the variants, with the total pressure loss coefficient as the object. Then the global optimal solution have been got using a multi-island genetic algorithm (MIGA) optimization method combined with sequential quadratic programming (NLPQL). Fig. 2 shows the comparison of the three profiles between the origin and the optimized. Fig. 3 shows the static pressure of optimized cascades. The comparison of object between the origin and the optimized is listed in Table 1, the results show that the aerodynamic performance of cascade profile improved.

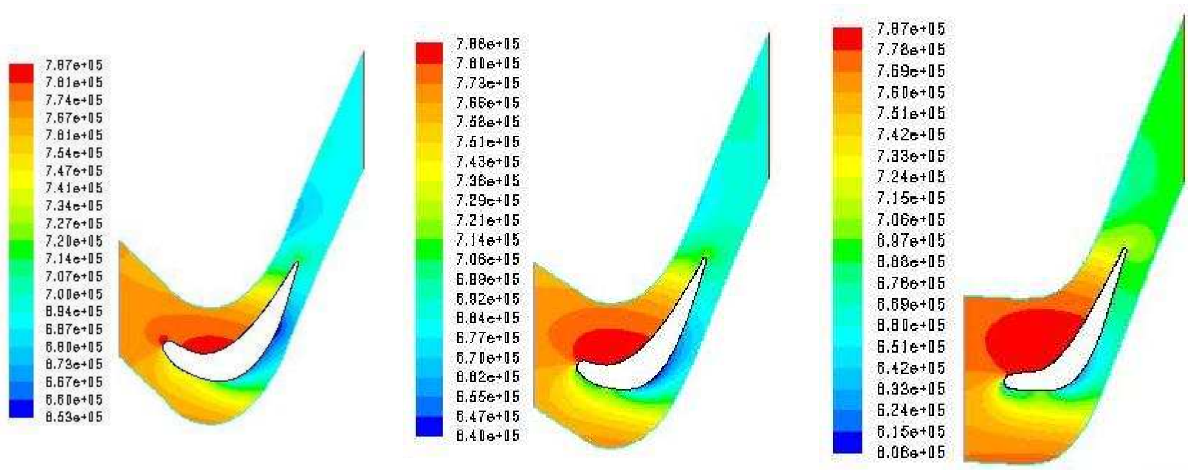
Table 1 Comparison of total pressure loss coefficient between the origin and the optimized

Section	Trend	Origin	Optimized	Relative improvement
Root	↓	0.107	0.065	39.25%
Middle	↓	0.094	0.077	18.09%
Tip	↓	0.162	0.121	25.31%



Root section Middle section Tip section

Fig. 2 Comparison of the three profiles between the origin and the optimized



Root section Middle section Tip section

Fig. 3 Static pressure of cascades

3 VCO of turbine blade

The VCO method is used to enhance the optimizing efficiency because the three-dimensional CFD of turbine blade costs high time complexity. We can select single section of blade, get the optimal profile by 2D optimization with parameter of profile as the variants, and then take 3D optimization with the optimal profiles as initial values. Fig. 4 shows the Flow chart of VCO of turbine blade.

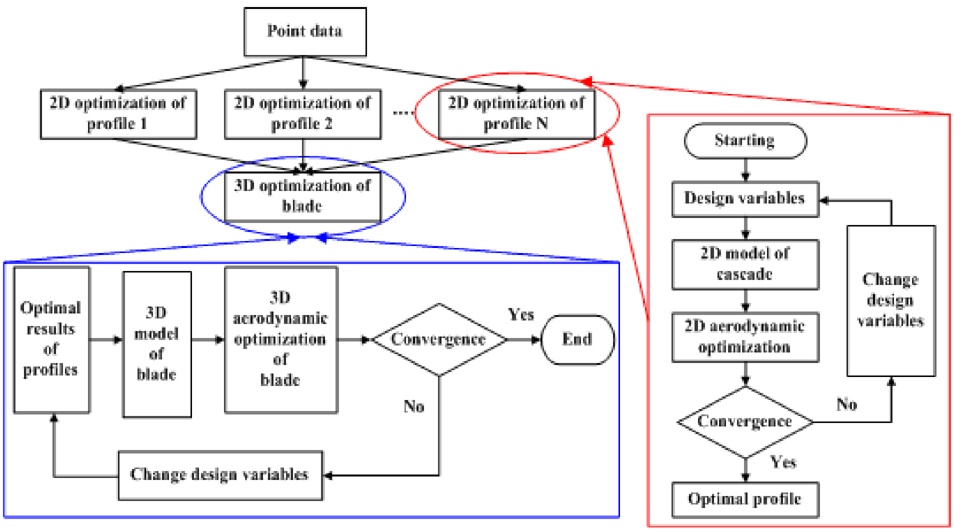


Fig. 4 Flow chart of VCO of turbine blade

Taking the parameters of 2D optimization as design variables, aerodynamic performance as object, MIGA optimization method combined with NLPQL as optimization algorithm, the optimal profiles by 2D optimization as initial values, the 3D optimization of turbine blade is carried out. Then another 3D optimization (full 3D optimization) with the same design variables, object and algorithm, but its initial value is same as the initial value of 2D optimization of cascade profiles. The comparison of optimization efficiency of these two optimization processes is listed in Table 2.

Table 2 Comparison of optimization efficiency

Optimization process		Object	Trend	Origin	Optimized	Relative improvement	Time cost [hour]	
VCO	2D	aerodynamic performance	↑	0.7970	0.8562	7.43%	29.4	646.5
	3D						617.1	
Full 3D		aerodynamic performance	↑	0.7970	0.8494	6.57%	890.4	

Conclusions

In this paper, VDO method is used to take aerodynamic optimization for turbine blade, such conclusions can be achieved:

1. Compared with the full 3D optimization under the same effect, the design period is shortened and the calculation cost is reduced by the variable complexity optimization method.
2. The 2D optimization based on five-order polynomial expression can improve the aerodynamic performance of turbine cascade.
3. Taking 2D optimal profiles as the initial values of 3D optimization, the optimal result is obtained faster.

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