Parametric modeling and stagger angle optimization of an axial flow fan

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Abstract. Axial flow fans are widely used in every field of social production. Improving their efficiency is a sustained and urgent demand of domestic industry. The optimization of stagger angle is an important method to improve fan performance. Parametric modeling and calculation process automation are realized in this paper to improve optimization efficiency. Geometric modeling and mesh division are parameterized based on GAMBIT. Parameter setting and flow field calculation are completed in the batch mode of FLUENT. A control program is developed in Visual C++ to dominate the data exchange of mentioned software. It also extracts calculation results for optimization algorithm module (provided by Matlab) to generate directive optimization control parameters, which as feedback are transferred upwards to modeling module. The center line of the blade airfoil, based on CLARK y profile, is constructed by non-constant circulation and triangle discharge method. Stagger angles of six airfoil sections are optimized, to reduce the influence of inlet shock loss as well as gas leak in blade tip clearance and hub resistance at blade root. Finally an optimal solution is obtained, which meets the total pressure requirement under given conditions and improves total pressure efficiency by about 6%.

1. Introduction

In the design of turbo-machinery blades, there are many components to be improved in terms of aerodynamics, structure and vibration etc. To design efficient aerodynamic blade shapes that reduce loss is still a challenging problem. Accurate flow analysis and multi-objective optimization are essential, and the two together require large computational resources. Cao dong bo [1] presents details of secondary development of GAMBIT for parametric modeling to improve the efficiency in his paper about pump optimization. Sasaki D et al [2] choose Matlab as the main framework of their multi-objective optimization and Adaptive Range Multi-Objective Genetic Algorithm as the optimizer. They consider a single stage for optimization in terms of computational time. Lee S Y et al [3] modify stacking line of the blade and find an optimum one to design a custom-tailored 3-dimensional blade for maximum efficiency. They also only calculate a single stage rotor-stator flow and use a spatially-varying time-step and implicit residual smoothing to accelerate convergence. Lee K S et al [4] modify stacking line as well as airfoil profile to enhance blade total pressure efficiency and they find that the modification of blade lean is more effective to improve efficiency rather than modifying airfoil profile.

In this paper, optimization of the stagger angle of rotor blade using a single-stage rotor-stator flow calculation is described. The airfoil profile has been optimized in advance and the stacking line
maintains the same, which is almost straight. The fluid computational domain was built and
discretized in GAMBIT, and following fluid calculation and analysis was carried out in FLUENT. The
optimization was realized in Matlab using fmincon function as optimizer, which can be found in
Matlab’s Optimization Toolbox and is suitable for constrained nonlinear multivariable optimization.

2. Model

2.1. Geometry and meshing
An axial flow fan with diameter of 800 mm is taken as the prototype in this paper. A new blade airfoil,
based on basic airfoil CLARK y, is designed. Inlet angle is determined by velocity triangle and outlet
angle confirmed using non-constant circulation method \cite{5}. The shape of airfoil center line is
constructed using triangle discharge of the loading distribution method \cite{6}. Model with the new rotor
blade airfoil is used as initial model of the optimization process. It contains a single stage, having 9
rotor blades and 8 stator blades, with operating point specified at flux rate of 21000m$^3$/h and rotational
speed of 1460 rpm. The hub and tip radius for the rotor is 210 mm and 395 mm respectively and that
of stator is 149 mm and 400 mm. Tip clearance of the rotor blade is 5 mm. The length of rotor and
stator is 360 mm and 420 mm. As shown in figure 1, the computational fluid domain only include
one-ninth of the rotor and one-eighth of the stator in terms of computing requirements and time. It is
set up in a parametric way and more details will be talked about in the following section 2.2.

![Figure 1. Geometric model.](image)

With the help of mixing plane approach and periodic boundary conditions \cite{7}, it is possible to
simulate flow-field of the whole fan using a partial model. In the mixing plane approach, each fluid
zone is treated as a steady-state problem. Flow-field data from adjacent zones are passed as boundary
conditions that are spatially averaged or "mixed” at the mixing plane interface. So the outlet face of
rotor does not have to coincide with the inlet face of stator. They don’t even need to share the same
area.

Due to the complexity of blade geometry, unstructured tetrahedral meshes are used around the rotor
and stator blade with size of 8 and 15 respectively, in terms of the balance of calculation accuracy and
computation time. EquiSize Skew of the elements is controlled within 0.9.

Boundary conditions are set with reference to the 11th example in FLUENT Tutorial Guide\cite{8}. Ideal
gas is used for the analysis, which models air as compressive fluid. Standard $k – \varepsilon$ turbulence model
is enabled. Mixing plane is created between the pressure outlet of rotor and the mass flow inlet of
stator. One-ninth of the flux rate is given at the mass flow inlet of rotor. Convergence criterion for the
energy equation maintains $10^{-6}$ and the others are reduced to $10^{-5}$.

2.2. Parametric modelling
Modeling parameterization is solved based on GAMBIT and a self-developed program (referred to as
Console). Similar implementation process can be found in reference \cite{1}.
A batch file is prepared in advance. It contains a start command of GAMBIT, which is written in following format:

\[ D:\Fluent.Inc\ntbin\ntx86\gambit.exe -r2.4.6 -id user_id -inputfile user.jou \]

Each time when Console wants to establish a new model with changed stagger angle parameters, it rewrites the batch file first with a new \textit{inputfile} name specified and then executes it. GAMBIT will be launched then with a specific temporary journal file passed to it. As for the temporary journal files, they copy content from one fixed GAMBIT template journal file precompiled.

The template journal file starts with parameter definition statements as follows:

\begin{verbatim}
$a = 0 
$b = 0 
$c = 0 
$title = "E:\angle"
$link = " "
$end1 = ".tur"
$end2 = ".msh"
$id1 = \text{title + NTOS($a) + $link + NTOS($b) +$link + NTOS($c) + $end1}
$id2 = \text{title + NTOS($a) + $link + NTOS($b) +$link + NTOS($c) + $end2}
\end{verbatim}

It can be seen from above that three variables are defined, i.e. $a$, $b$ and $c$. These three variables are defined for the decrease control of stagger angle and value of them will be changed every time when content of template journal file being copied to a temporary journal file.

Generation process of the temporary journal file can be described with more details as follows:

The Console first generates three-dimensional coordinates of vertexes which are used to construct the contour line of rotor blade airfoil section. It will then create a temporary journal file, writing the coordinates to it and copying content of template journal file in the below. This temporary journal file will be passed to GAMBIT when the latter being launched in batch mode and directs the modeling process.

The principle for the entire modeling process is as follows:

Contour lines of the 6 airfoil sections are generated first, and surfaces of the rotor blade are constructed through these contour lines. With these surfaces, we can further stitch out body of the blade and carry out some Boolean operations to create the final computational fluid domain. As fluid domain is cyclical in rotational direction, a partial fluid domain can be constructed with rotational periodic boundary specified to replace the original whole model. Faces set as periodic boundary have to be linked as pairs to insure identical face mesh. These pairs will be identified in FLUENT, determining the number of copy needed in the circumferential direction to simulate the whole model.

After the completion of geometric modeling and meshing, mesh file will be generated and written to specified path. In this way, parametric modeling is realized with insurance that model obtained at each optimization iteration is of same geometric structure and mesh size but with different stagger angle.

3. Optimization

3.1. Process automation

Figure 2 shows how calculation process is planned during optimization. Area I, circled by dotted lines, is a process controlled by Console program mentioned above and area II is led by Matlab Optimization Toolbox.

The Console writes airfoil data files and calls GAMBIT in batch mode to generate geometric model and divide mesh for the following simulation calculation. When mesh file is written to allocated place, Console program takes it as a signal to launch FLUENT for flow calculation. Boundary conditions and other calculation parameters are written in FLUENT TUI (Text User Interface) language and saved in
a template file which is also post-fixed with jou. This template journal file is passed to FLUENT every time at launch to guide calculation process and post-operation, such as outputting pressure and moment results to specific text files. Once these result files are created, they can be immediately detected by Console program, indicating that the current computation cycle is finished. The Console will then calculate the corresponding fan total pressure efficiency and write it to an output file. The efficiency data file will be read by Matlab Optimization Toolbox to decide whether optimization criterion is satisfied, if not, new stagger angle parameters will be generated and Console program will be launched again for the whole calculation process (i.e. area I in figure 2) to restart and march another optimization step.

![Figure 2. Optimizing process.](image)

3.2. Reason for optimization
Six airfoil sections are used when shaping the twisty three-dimensional model of the blade (see figure 3). The radiuses they correspond to are listed in following table 1.

| Section | A   | B   | C   | D   | E   | F   |
|---------|-----|-----|-----|-----|-----|-----|
| Radius (m) | 0.21 | 0.22 | 0.265 | 0.305 | 0.35 | 0.395 |

![Figure 3. Airfoil sections instruction.](image)
Figure 4. Contours of Axial Velocity on surface with Y Coordinate of -0.03m.

As shown in figure 4, an Iso-Surface is set up to observe axial velocity distribution near leading edge of the rotor blade upper part. Negative Y axis is the direction of rotation. Positive velocity emerges in upper part of the Iso-Surface near blade surface, indicating the existence of reverse flow. Reverse flow disturbs the inlet flow direction like applying a rational inlet pre-swirling. But inlet pre-swirling is not considered in theoretical calculation of inlet flow angle using routine velocity triangle. It also can be seen from figure 4 that, axial velocity distribution is not uniform. It is also not accurate to treat axial velocity as uniform in theoretical calculation.

It is difficult to keep blade stagger angle consistent with inlet flow direction through theoretical calculation since, affected by reverse flow, velocity distribution of the inlet flow is very complex now. Thus, adopting optimization method to explore proper stagger angle seems a good choice.

To explore the best stagger angle, making air flow remain the ideal state after bypassing rotor blade, three variables are introduced to the optimization process to adjust stagger angle together. Optimization process accords to the principle of maximum efficiency. In connection with figure 3, the first variable determines the stagger angle decrease of section $A$ and $B$ (considering these two sections are quite close and together define the shape of the blade root), the second one controls the stagger angle decrease of section $F$, i.e. rotor blade tip, and the last one is responsible for section $E$. As for section $C$ and $D$, linear interpolation is used to make the amplitude of their stagger angle decrease changes between that of B and E. This method fully considers different situations at the six airfoil sections, i.e. they may have different angle of attack.

### 3.3 Optimization strategy

The optimization problem is solved using Matlab Optimization Toolbox. *Fmincon* function is chosen to be the optimizer. It attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate and is generally referred to as constrained nonlinear optimization or nonlinear programming.

*Fmincon* has a variety of syntax and the following one is used:

$$x = \text{fmincon}(\text{fun},x0,A,b,Aeq,beq,lb,ub,\text{nonlcon},\text{options})$$

With the help of last parameter *options* in this syntax, optimization options can be added to the optimizer. Specific definition of options in this optimization problem is as follows:

```
options=optimset('Algorithm','interior-point','DiffMinChange',0.5,'TolX',0.001,'TolFun',0.0001)
```
Formula above tells the optimizer to choose algorithm of *interior-point* and forces the minimum variation of variables at each intermediate calculation to be 0.5. *TolX* and *TolFun* refer to the termination tolerance on variables and function value respectively.

The goal of optimization is to make the most of efficiency and meet pressure requirement at the same time. Pressure requirement of the fan under flux rate of 21000 m$^3$/h and rotational speed of 1460 rpm is 590 Pa for static pressure and 670 Pa for total pressure. Considering dynamic pressure is essentially unchanged, it’s enough considering static pressure requirement alone. When static pressure meets the standard, the higher efficiency, the better.

4. Results

Models analyzed in the optimization process have a uniform target static pressure of 780 Pa and target total pressure of 860 Pa. And the rotor blade stacking line and thickness remain unchanged. Three-variable optimization is explored. Finally, an optimal solution is found. Iteration process of the stagger angle decrease is shown in figure 5 below.

![Figure 5. Iteration process of three variables.](image)

As we can see in figure 5, when an optimum is found, the number of iterations does not equal with the total calculation times. In general, Optimization Toolbox solver (which is *fmincon* function in this case) iterates to find an optimum, it begins at an initial value $x_0$ (which is combination of (0,0,0) in figure 5), performs some intermediate calculations that eventually lead to a new point $x_1$, and then repeats the process to find successive approximations $x_2, x_3, ...$ of the local minimum. Processing stops when criteria are satisfied after some number of iterations$^{[10]}$.

Result comparison of the initial and optimal models is shown in table 2 below. The optimal model meets the static pressure requirement and efficiency of which is also satisfactory. Fan total pressure efficiency has been improved by about 5.75%. The optimal combination of stagger angle decrease also shows three variables’ respective proportion in impact on the efficiency. That’s to say, installation angle decrease of section $E$ has a better effect on the increase of efficiency than the others.
Table 2. Calculation results comparison.

| Optimization         | Stagger angle decrease of section (°) | sp (Pa) | dp (Pa) | tp (Pa) | e (%) |
|----------------------|---------------------------------------|---------|---------|---------|-------|
| A, B                 |                                       | 0       | 0       | 651.28  | 78.88 | 730.16 | 69.24 |
|                      |                                       | 0.05677 | 0.05529 | 0.06011 | 650.37 | 78.88  | 729.25 | 69.35 |
|                      |                                       | 0.07809 | 0.07430 | 0.08577 | 650.59 | 78.88  | 729.47 | 69.41 |
|                      |                                       | 0.35183 | 0.32794 | 0.42368 | 646.20 | 78.88  | 725.08 | 70.09 |
| Intermediate-        |                                       | 0.76737 | 0.71156 | 0.92944 | 637.62 | 78.87  | 716.49 | 70.94 |
| iterations           |                                       | 2.44628 | 2.26985 | 2.98965 | 597.58 | 78.84  | 676.42 | 74.71 |
|                      |                                       | 2.41204 | 2.23719 | 2.93686 | 598.50 | 78.84  | 677.34 | 74.57 |
|                      |                                       | 2.50900 | 2.31430 | 2.92730 | 597.27 | 78.84  | 676.11 | 74.64 |
|                      |                                       | 2.90387 | 2.62464 | 2.91791 | 594.70 | 78.84  | 673.54 | 74.98 |
| After/optimal        |                                       | 2.89310 | 2.61628 | 2.91781 | 594.73 | 78.84  | 673.57 | 74.99 |

* sp: static pressure; dp: dynamic pressure; tp: total pressure; e: total pressure efficiency

Figure 6-8 focus on the basis of efficiency improvement with comparison of optimal model to the initial one. From figure 6 we can see, decrease of stagger angle depresses the turbulence of flow at the suction side of rotor blade, which is more comprehensively reflected in figure 7. Figure 8 shows that the optimal blade shape has a better static pressure distribution at the leading edge of rotor blade suction side, indicating more consistency in blade stagger angle and inlet flow direction.

Figure 6. Contours of Turbulent Kinetic Energy near blade on surface with radial coordinate of 0.39 m.

Figure 7. Contours of Turbulent Kinetic Energy at the suction side of rotor blade.
5. Conclusions

Stagger angle adjustment is explored in this paper, which is acted on six sections of the rotor blade in radial direction independently. With the help of Matlab Optimization Toolbox, we can undertake linkage change of multiple variables and explore the coupling effect between them, which makes the optimization more detailed and targeted.

Parametric modeling and automatic computing is another major task solved in this paper. It is the prerequisite of the optimization process and is of great significance. It has greatly reduced the workload and also paved the way for further exploring coupling relationship between more factors influencing fan performance.

The stagger angle optimization in this paper is limited within three degrees, for the sake of not causing excessive drop of the static pressure. This restriction can be relaxed in further study to obtain higher fan efficiency.

6. References

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