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Design optimization of low-speed axial flow fan blade with three-dimensional RANS analysis †

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Abstract

This work presents a numerical optimization procedure for a low-speed axial flow fan blade with polynomial response surface approximation model. Reynolds-averaged Navier-Stokes equations with SST turbulence model are discretized by finite volume approximations and solved on hexahedral grids for flow analyses. The blade profile as well as stacking line is modified to enhance blade total efficiency, i.e., the objective function. The design variables of blade lean, maximum thickness and location of maximum thickness are selected, and a design of experiments technique produces design points where flow analyses are performed to obtain values of the objective function. A gradient-based search algorithm is used to find the optimal design in the design space from the constructed response surface model for the objective function. As a main result, the efficiency is increased effectively by the present optimization procedure. And, it is also shown that the modification of blade lean is more effective to improve the efficiency rather than modifying blade profile.

Keywords: Axial flow fan; Design optimization; Navier-stokes equations; Stacking line; Lean; Maximum blade thickness; Response surface method

1. Introduction

Numerical optimization techniques based on three-dimensional Reynolds-averaged Navier-Stokes equations become practical for the design of turbomachinery blades with the aid of development in computing power in the last decade. Application of the optimization techniques has enhanced the performance of turbomachinery in terms of weight, torque, efficiency, pressure, surge margin, etc. by changing stacking line, blade profile, etc.

Effects of blade stacking line modification have been reported by Sasaki and Breugmans [1], Wadia et al. [2], and Gallimore [3]. They suggested that blade performance can be increased effectively by modifying three-dimensional stacking line. Blade shape optimization using response surface approximation (RSA) was reported by Ahn and Kim [4], Jang and Kim [5], and Seo et al. [6]. Samad et al. [7] has reported on the blade stacking line modification to optimize a compressor blade using several different surrogate models. The above mentioned studies report that the efficiency can be increased by reducing separation zone, modifying corner vortex, etc. Polynomial response surface method [8] being simple to apply, is getting widely used [4-6, 9].

The optimization considering blade profile defined by Bazier curve is reported by Burguburu et al. [10]. Multi-objective optimization of a compressor blade with efficiency and total pressure as objectives was performed by Benini [11], who considered variables of blade stacking line and thickness of blade profile. Fan blade was optimized by Idahosa et al. [12] through an automated optimization procedure. Effect of maximum camber location on a transonic compressor blade was reported by Chen et al. [13]. They

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studied numerically and suggested that efficiency can be increased changing the airfoil shape.

The present effort describes numerical shape optimization of a low-speed axial flow fan blade with NACA65 airfoil. The blade stacking line, maximum thickness and location of maximum thickness are considered as design parameters. The total efficiency has been employed as an objective function, and the RSA model is constructed to find an optimum design. Reynolds averaged Navier-Stokes (RANS) analyses have been used to evaluate values of the objective function.

2. Numerical analysis

The reference fan blade (NACA65) is shown in Fig. 1 and its major specifications are listed in Table 1. Hexahedral grid system is employed. To find the optimum number of grids, grids dependency test has been carried out and 6.3×10^5 has been selected as the optimum number of grids. The grids near the leading edge (LE) are shown in Fig. 2. And, Fig. 3 shows the results of grid dependency test. As for better implementation of SST model, near wall grid resolution is checked to keep y+ value of the first grid less than unity.

The commercial software ANSYS CFX 11.0 [15] is used for this problem. This software contains Bladegen, Turbogrid, CFXpre, CFXsolver and CFXpost. In Bladegen, blade profile is generated and the profile is exported to Turbogrid for mesh generation. The mesh is then imported in CFXpre for boundary and initial condition definitions and finally run in CFXsolver which solves three-dimensional steady incompressible RANS equations. Governing equations are discretized using finite volume approximations, and shear stress transport (SST) model is used as a turbulence closure.

Inlet mass flow for a single blade is set to 0.307 kg/s and exit pressure is set to 0.0 Pa. RMS value is set 1.0E-5 for convergence criteria with automatic time steps. Automatic time step is calculated as 0.2/ω, where ω is the angular velocity of blades. The converged solutions are obtained after approximately 400 iterations. One of the nine blades is selected for numerical analysis that uses periodic boundary conditions. Uniform velocity profiles are assumed at the inlet, and constant pressures are applied at the exit boundary. The working fluid is 20°C air. To obtain a completely converged solution for the present analysis, the CPU time required was approximately 12 hours with a Pentium-IV, 3.0 GHz processor.

Table 1. Specifications of reference fan blade.

Flow Coefficient	0.41
Total Pressure Coefficient	0.3
Rotor Rotation Frequency	1000 rpm
Tip Radius	287.5 mm
Hub-Tip Ratio	0.52
Inlet Angle at Rotor Tip	68.8 degrees
Outlet Angle at Rotor Tip	63.8 degrees

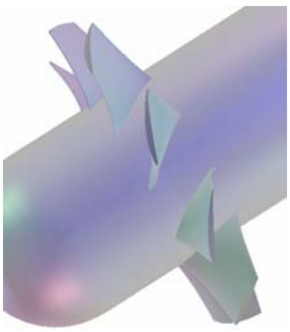


Fig. 1. Reference blade shape.

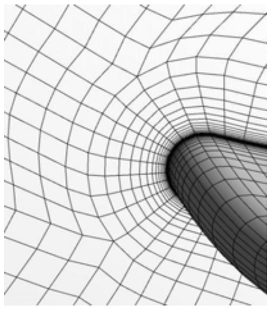


Fig. 2. Grids near leading edge.

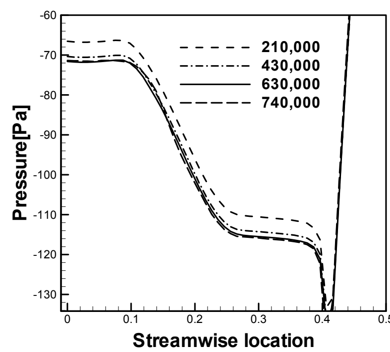


Fig. 3. Grid-dependency test.

3. Objective function and design variables

The objective of the problem is to enhance total efficiency (η), which is defined as:

$$\eta = \frac{\left(p_{t,out} - p_{t,in}\right) \cdot Q}{\tau \cdot \omega} \qquad (1)$$

where, P_t is the total pressure, and the subscripts, *in* and *out*, respectively indicate inlet and exit of the fan. Q is the flow rate, τ and ω are torque and angler velocity, respectively.

Three design variables are selected related to stacking line and blade profile. The straight stacking line is inclined by lean (δ), and definition of the lean is shown in Fig. 4. The lean is the movement of airfoil sections normal to the chord line.

The blade airfoil profile is changed using the third-order Bezier curve as shown in Fig. 5. The curve is defined by third-order polynomial and the control points of the Bezier curve are P1, P2, P3 and P4. For thickness control, P2 is changed while the other points are fixed. The main advantage of parameterization of the blade curves by Bezier curve is that some limited number of points called control points can control the curves and the curves are smooth and free from discontinuities. The blade shape can be changed

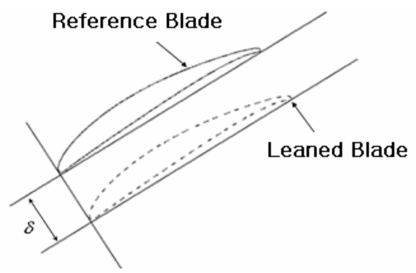


Fig. 4. Definition of blade lean.

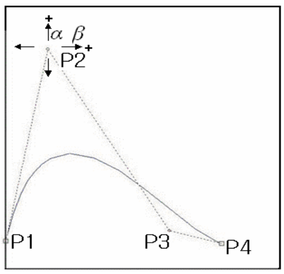


Fig. 5. Control of maximum thickness and maximum thickness location by Bezier curve.

by moving the control points. A Bezier curve of order n is defined by the Bernstein polynomials:

$$C(t) = \sum_{i=0}^{n} B_{n,i}(t) P_i \qquad (2)$$

Here, Bezier blending function is defined by

$$B_{n,j}(t) = \binom{n}{j} t^i (1-t)^{n-1} \qquad (3)$$

where t denotes the parameter of the curve normalized in [0 1] and P_i are the coordinates of the control points. The control points of Bezier curve are considered variables.

In Fig. 5, if P2 is moved vertically, the blade thickness is changed, and if P2 is moved horizontally, the location of maximum thickness is changed. Hence, two design variables, α and β, are required to control the blade shape. Positive sign of α indicates increase of the blade thickness, and similarly positive sign of β indicates movement of the maximum thickness location towards trailing edge.

4. Numerical optimization

Response surface method is a series of statistical and mathematical techniques; generation of data by numerical computations or experiments, construction of response surface by interpolating the data, and optimization of the objective function on the surface. Although response surface method was devised to obtain empirical correlations from the experimental data, the ability to reduce the number of experiments let this method be applied widely to the optimization problems.

The response surface is generally approximated using a second-order polynomial, which can be written as follows:

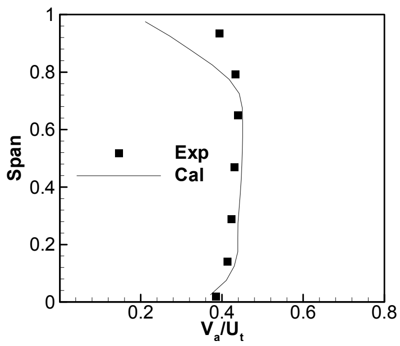
$$f = \beta_0 + \sum_{j=1}^{n} \beta_j x_j + \sum_{j=1}^{n} \beta_{jj} x_j^2 + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ i \neq j}}^{n} \beta_{ij} x_i x_j \qquad (4)$$

where f is the response, x is the design variable, n is the number of design variables, and β_o, β_1, etc. are regression coefficients. To determine the coefficients, standard least-squares regression is used. To estimate the significance of each individual in the quadratic polynomial coefficient, ANOVA (analysis of variance) and regression analysis are used as the measure of the uncertainty in the coefficients to increase the efficiency of the response surface.

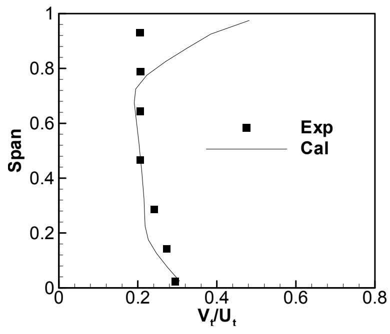
The values of the objective function are computed at design points generated by a design of experiment technique using RANS analysis, and the values are used to generate RSA model. A gradient based search algorithm is used to find the optimal points in design space. If the design points are outside the design space, the design space is changed and again whole procedure is followed.

5. Results and discussion

For the validation of numerical solutions, computational results are compared with experimental data [14] as shown in Fig. 6, where spanwise distributions of axial and tangential velocity (Fig. 6(a)) components are plotted. The computational results show good agreement with the experimental data except in the region near blade tip. The discrepancy in this region is probably due to the tip clearance vortex which can not be correctly predicted by the turbulence model.



(a) Axial velocity



(b) Tangential velocity

Fig. 6. Distributions of axial and tangential velocity components downstream of the fan rotor.

For design optimization, it is important to find the feasible design space which is formed by variable ranges in which the calculations are to be performed. Some preliminary calculations are done to find the initial design space and full factorial design [8] is used to find the design (sampling) points for computations. The ranges of design variables are presented in Table 2. The reference blade has the values of the design variables: α =0, β =0 and δ =-19^0. Twenty seven design points are selected through three-level full factorial design and objective function values are evaluated by RANS analysis.

Table 3 shows the RANS computed objective function values for the reference and the optimized blades. The optimized blade shows that the total efficiency is increased to 87.40%. Table 4 shows values of the design variables at the optimum point.

Table 2. Design space.

Variables	Lower Bounds	Upper Bounds
α	-0.004m	0.003m
β	-0.01m	0.02m
δ	-35^0	-3^0

Table 3. Results of RANS calculations.

Design	Efficiency	Increment
Reference	85.90 %	-
Optimum	87.40 %	1.50 %

Table 4. Values of design variables at the optimum point.

Surrogate	α	β	δ
RSA	-0.0039m	0.001m	-16.54^0

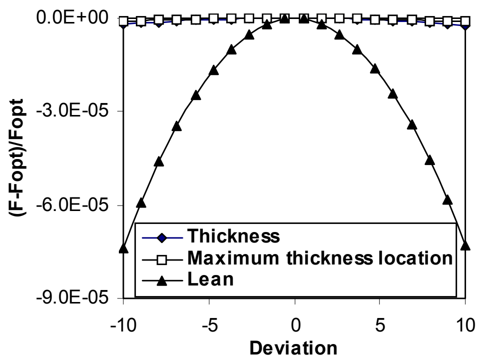
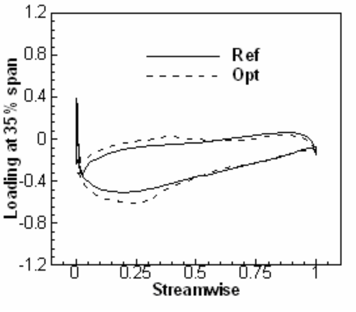
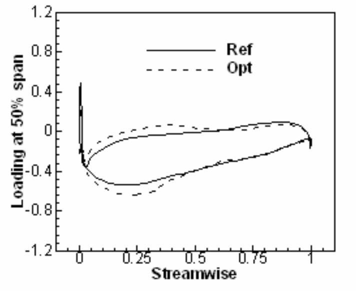


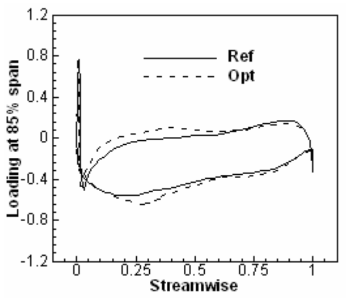
Fig. 7. Sensitivity of objective function.



(a) 35% span



(b) 50% span



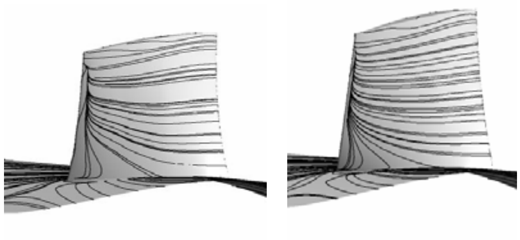
(c) 85% span

Fig. 8. Blade loading.

Fig. 7 shows the sensitivity of objective function with the 10% deviation of variables from optimal point. RSA model is used to evaluate objective function values. This figure shows that the lean is more responsible to increase the efficiency than the other variables at near optimal point.

Blade loading defined by the work done by the blade on fluid is plotted at 35%, 50% and 85% of blade span as in Fig. 8. Obviously, the blade loading has been increased for the optimized blade as compared to the reference blade near the upstream location.

The streamlines near the suction surface are shown in Fig. 9. The optimum shape shows the movement of separation lines towards the downstream direction. It reduces the losses, hence increases the efficiency.



(a) Reference shape (b) Optimum shape

Fig. 9. Streamlines near suction surface.

6. Conclusion

A low-speed axial flow fan blade has been optimized to enhance total efficiency by RANS analysis and response surface approximation. Blade lean, maximum thickness and location of maximum thickness are changed for the optimization. By the optimization blade efficiency is increased by 1.5%. The enhancement of efficiency is due to the change in flow structure through the passage. It is found that the total efficiency of the fan is much more dependent on the lean of blade stacking line than the other variables, i.e., blade maximum thickness and location of maximum thickness.

Acknowledgement

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