Performance and Efficiency Improvement of an Axial Flow Fan by Combining the FANDAS and the PIAnO Codes

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Abstract: The present paper deals with the optimization study of a variable-pitch axial flow fan by combining fan design method of the FANDAS (FAN Design and Analysis System) code and optimization algorithm of the PIAnO (Process Integration, Automation and Optimization) code. The FANDAS code is used as fan design program to design 3D fan rotor blade geometry and to predict designed fan's performance and efficiency, and it is also used as simulation engine for fan design optimization problem. The PIAnO code is used as optimization program to apply a function-based optimization algorithm to the FANDAS code and to find the optimal fan design solution for efficiency maximization. In this optimization study, spanwise camber, stagger angles and chord lengths of axial flow fan are selected as design variables and the design constraints are set to design flow capacity, total pressure, power and blade angles, solidities. Through the design optimization by combining the FANDAS and the PIAnO codes, optimal fan rotor blades are obtained and then they are coupled with existing outlet guide vanes to construct the final fan stage. Computational fluid dynamics (CFD) analyses are conducted to verify the performance and efficiency of the optimal fan design, and the CFD calculation results are matched well with the FANDAS predictions for performance and efficiency of optimal fan. The CFD results also show that the optimal fan design gives the efficiency improvement of about 6.7% compared to the initial design. Furthermore, the FANDAS performance predictions of the optimal fan under variable-pitch conditions show that the optimal fan can be operated with wide flow capacity range between 2000 and 5000 m^3/min and high efficiency above 80 % by adjusting fan rotor blade pitch angle.

1 INTRODUCTION

Axial flow fans are key flow elements of various ventilation, air conditioning and energy systems in industrial, commercial and residential fields. Recent technical issue of axial flow fan is to improve fan performance and efficiency because worldwide climate change and carbon neutral trends call for more energy saving of all kinds of machines and equipment. Since variable-pitch axial flow fans are operated by setting fan blade setting angle automatically for maintaining high efficiency over wide flow capacity range, they have been being developed by many fan industries and introduced in fan application systems. In high-efficiency axial flow fan design, it is very critical for fan designer to optimize 3-D fan blade geometry because air flow motion on fan blade surface affects severely the aerodynamic characteristics and efficiency of the fan. For this reason, .many researches have applied optimization techniques to design and optimize fan blade geometry for high efficiency fan development (Angelini, 2017; Edward, 2021).

Thus, in order to maximize fan efficiency, the present paper proposes a new variable-pitch axial flow fan design method coupled with optimization algorithm. The optimal fan designed by the present method is verified by using the CFD simulation and its variable-pitch operation and performance characteristics are predicted and examined.

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2 FAN DESIGN AND PERFORMANCE PREDICTION

The present study employs the FANDAS code for designing 3D fan rotor blade geometry and predicting the fan performance and efficiency. With the use of the FANDAS code, fan blade sections are designed from the camber, the stagger angles and the chord length as design variables and then 3D fan blade geometry is constructed by the stacking of blade section elements along blade span height from hub to tip. The camber line of blade section is determined by single circular arc formula with given camber angle and NACA 65 airfoil thickness distribution is added onto the camber line to construct blade element profile (refer to Figure 1).

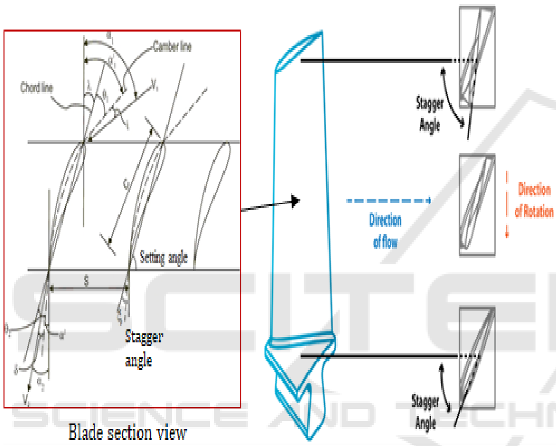

Figure 1: Nomenclature for blade design parameters.

The FANDAS code can also predict the performance, power and efficiency of designed fan by using the through-flow analysis method of the streamline curvature-computing scheme for the pitch-averaged radial equilibrium equation of flow motion with total pressure loss models (Novak, 1967).

$$\frac{dV_m^2}{dr} + A(r)V_m^2 = B(r) \quad (1)$$

$$A(r) = 2sin^2\beta[-\frac{sin\phi}{V_m}\frac{dV_m}{dm} + \frac{cos\phi}{r_m} + \frac{csc^2\beta}{2}\left(\frac{1}{Q}\frac{dQ}{dr}\right) + \frac{1}{2}\frac{d(cot^2\beta)}{dr} + \frac{cot^2\beta}{r} + \frac{2\Omega}{V_m}cot\beta] \quad (2)$$

$$B(r) = 2sin^2\beta[\frac{1}{Q}\frac{d(IQ)}{dr} + \frac{\Omega^2 r^2}{2}\left(\frac{1}{Q}\frac{dQ}{dr}\right)] \quad (3)$$

where V_m, β, r_m and ϕ represent meridional flow velocity, relative flow angle, streamline curvature radius and slope, and I, Ω and Q mean rothalpy, angular rotational speed and entropy function.

The FANDAS code was developed and commercialized by the authors and its details are described in the reference.(Lee, 2021; Kyungwon Tech. 2017).

The FANDAS code is applied for designs and performance predictions of axial flow fans without or with blade sweep. Three dimensional geometry of axial flow fan blade rotor is designed by the FANDAS code and depicted in Figure 2, and the fan performance curves are also shown in Figure 3. Comparing the performance prediction and the test results of axial flow fan (Hurault, 2010), the FANDAS code can be considered as reliable tool to predict overall fan performance over entire flow capacity range except at very low flow condition causing stall or surging.

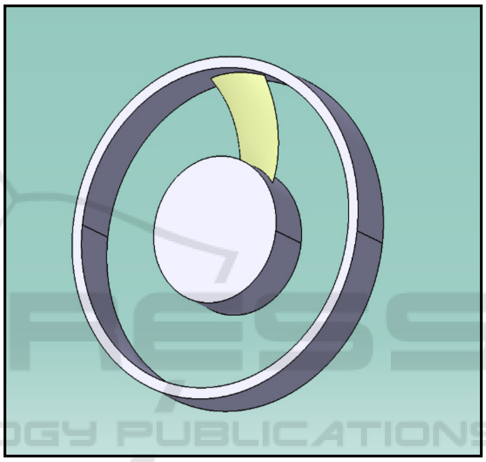
Figure 2: Fan blade rotor with 25 deg. Sweep.

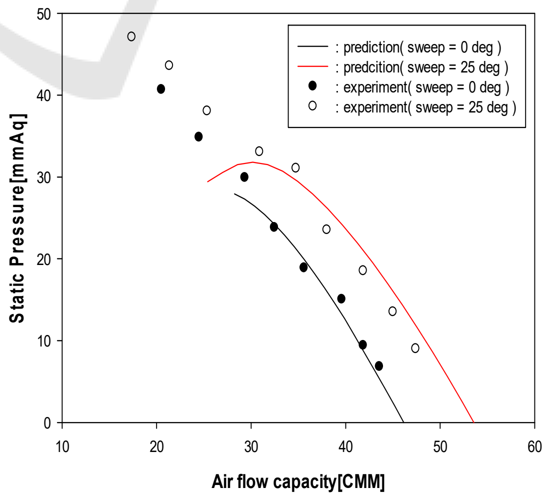

Figure 3: Performance curves of swept fans.

The present study applies the FANDAS code in the performance prediction of a variable pitch axial flow fan designed with camber and stagger angles of fan blade section as free design variables to construct 3D fan rotor geometry. Figure 4 shows the spanwise distributions of camber and setting angles (setting angle = 90º – stagger angle) over blade span height. Using the distributions of blade angles of Figure 4, the present study designs and constructs twisted fan rotor blades as shown in Figure 5. Figure 6 shows the performance prediction results of a variable pitch axial flow fan designed with the camber and the stagger angles of Figure 4. As shown in Figure 6, the FANDAS predictions are favorably matched with the test results (van der Spuy, 1997) at different fan-blade pitch conditions when the setting angle of blade hub is set to 25, 35 or 45 deg.

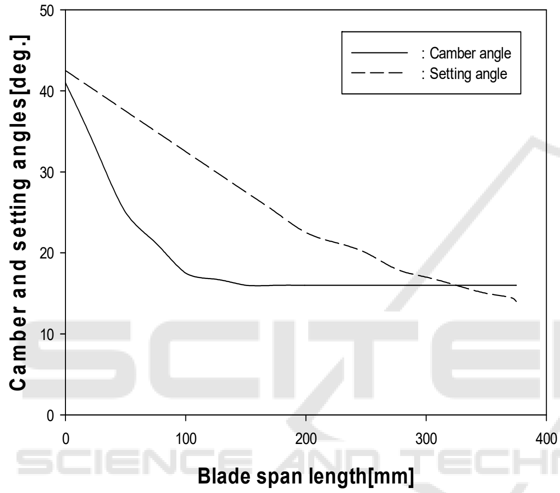

Figure 4: Camber and setting angle distributions.

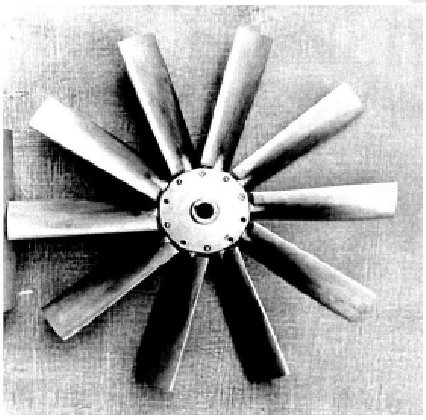

Figure 5: Rotor blades of a variable pitch fan.

The comparisons between the FANDAS prediction and the measurement results imply that the FANDAS code can be used as the design and performance prediction tool of axial flow fan with high prediction accuracy and then can be a suitable as simulation engine of design optimization problem.

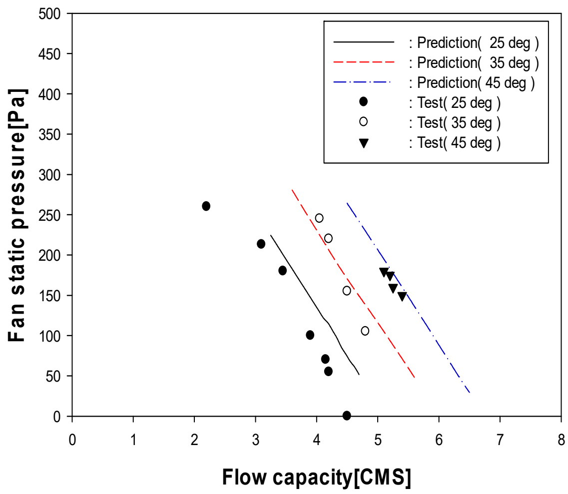

Figure 6: Performance curves of variable pitch fan.

3 THE PRESENT FAN DESIGN OPTIMIZATION AND VERIFICATION

The present study uses the FANDAS code as simulation engine in constructing the design optimization problem for efficiency (η) maximization of axial flow fan. As shown in Figure 7, the FANDAS code is incorporated with Hybrid Metaheuristic Algorithm (HMA) of the PIAnO code (PIDOTEC, 2021) as optimization technique and some mathematical formulations are made by using camber and stagger angles as design variables (Kim, 2022. It is noted that the HMA combines two different metaheuristic algorithms, differential evolution (DE) and cuckoo search (CS), using bi-population concepts.

In the presnt design optimization study, objective function is defined as the total pressure efficiency of fan, which is predcited by the FANDAS code, and design variables are the camber angles (θ_c), the stagger angles (ξ) and the chord lengths (c) fan rotor blade sections, so optimization problem is formulated as

$$\text{Optimize } \theta_c(\text{r}), \xi(\text{r}) \text{ and c(r) to maximize } \eta \quad \text{With constraints in Table 1} \tag{4}$$

Here the camber and the stagger angles are defined as design variables at five blade span locations, while the chord lengths are defined as design variables at the three locations of hub, mid-span and tip. For smooth change of chord length along blade span, the present study set the chord lengths at three locations of hub, mid span, and tip, and, at the point between which the blade angles are defined; the chord length is obtained by parabolic interpolation of chord lengths at the three locations.

The determined blade angles and chord lengths are used as input data for the performance prediction by through-flow analysis of the FANDAS code. The present design optimization study also employs the design constraints for design flow capacity, total pressure, shaft power and flow angles angles, solidities (chord length/blade spacing) of blade sections at different radial locations. The design variables and the design constraints of the present optimization problem are summarized in Table 1.

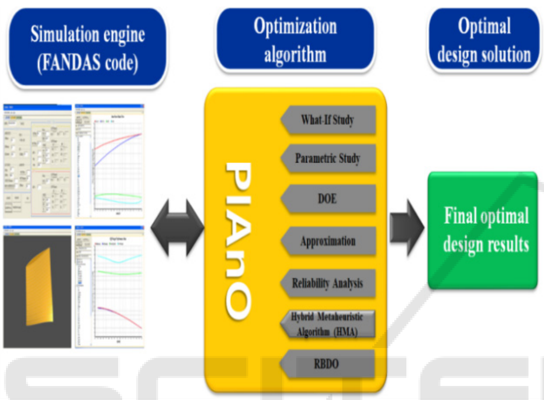

Figure 7: Optimization scheme of axial flow fan.

Table 1: Design variables and constraints for axial fan efficiency maximization.

Find X_1, X_2 ,…. ,X_{13} to maximize η_T =f(X_1,X_2 , .. ,X_{13})	
Design variable	Description
X_1 [deg.]	Camber angle at 0% span height (hub)
X_2 [deg.]	Camber angle at 25% span height
X_3 [deg.]	Camber angle at 50% span height (mid)
X_4 [deg.]	Camber angle at 75% span height
X_5 [deg.]	Camber angle at 100% span height (tip)
X_6 [deg.]	Stagger angle at 0% span height (hub)
X_7 [deg.]	Stagger angle at 25% span height
X_8 [deg.]	Stagger angle at 50% span height (mid)
X_9 [deg.]	Stagger angle at 75% span height
X_{10} [deg.]	Stagger angle at 100% span height (tip)
X_{11} [mm]	Chord length at hub
X_{12} [mm]	Chord length at mid-span
X_{13} [mm]	Chord length at tip
Design constraints	Fixed design parameters
Q = 3300 [m^3/min]	Rotation speed = 1200 [rpm]
650 < P_T < 850 [Pa]	Tip diameter = 1.52 [m]
Power < 55 [kW]	Hub to tip ratio = 0.33
0 < X_1~X_{10} < 90 [deg.]	No. of rotor blades (Z_b) = 8
$0.5 < \frac{X_{11}}{2\pi r_h/Z_b} < 2.5$	Tip clearance size = 5.0 [mm]
$0.5 < \frac{X_{12}}{2\pi r_m/Z_b} < 2.5$	
$0.5 < \frac{X_{13}}{2\pi r_t/Z_b} < 2.5$	

Applying the present optimization technique to an axial flow fan's efficiency maximization problem of Table 1, several iterative calculations are carried out and the design variables and the design constraints are converged during searching optimal design solution. After the several iterative computations, optimal design variables are obtained and the objective function is finally calculated as shown in Table 2. The optimal camber angle is higher than the initial design over entire blade span while the optimal stagger angle at hub is lower than the initial design, which is designed by free vortex concept (Dixon, 2014). The optimal chord length is smaller than the initial design and its magnitude decreases from tip to hub. Optimal fan rotor blade geometry is constructed by the FANDAS code with the design variables (refer to Figure 8); the efficiency of optimal fan is improved by 6.7 % when compared with the initial design.

Table 2: Optimal design variables and objective function.

Design variable	Optimal value	Initial value
X_1 [deg.]	18.63	31.43
X_2 [deg.]	14.83	13.68
X_3 [deg.]	11.83	7.77
X_4 [deg.]	9.64	5.52
X_5 [deg.]	8.27	4.59
X_6 [deg.]	36.23	26.91
X_7 [deg.]	47.80	47.44
X_8 [deg.]	56.63	57.96
X_9 [deg.]	62.71	64.20
X_{10} [deg.]	66.06	68.30
X_{11} [mm]	150.00	240.00
X_{12} [mm]	162.78	240.00
X_{13} [mm]	218.95	240.00
Objective function(η_T) [%]	85.78	79.11

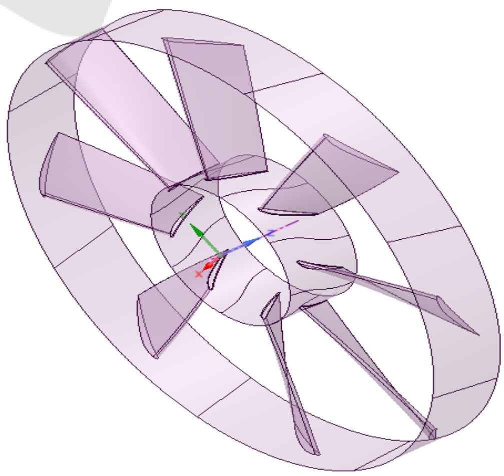

Figure 8: Optimal fan rotor blade geometry.

In order to verify the optimal fan design, CFD modelling is also made with structured mesh system in flow domain of the optimal fan stage (optimal fan rotor with outlet guide vane) and numerical calculations are carried out by the SIMERCIS MP code (Kyungwon Tech, 2022) with MRF scheme and k-ε turbulence model. Figures 9 and 10 show overall total pressure and efficiency curves of optimal fan, and the FANDAS predictions are matched well with the CFD results. As shown in Figure 9, optimal fan model shows lower total pressure at design point than the design constraint (P_T < 850 Pa) and wide operation range from 2700 to 3700 m^3/min. In Figure 10, the efficiency of optimal fan model is 85.8 % which is fairly compared with the CFD result of 82.8 % and is much higher than the initial design of 79.1 % (refer to Table 2). Total efficiency of optimal fan model is also maintained above 80% in wide flow capacity range between 2700 and 4000 m^3/min.

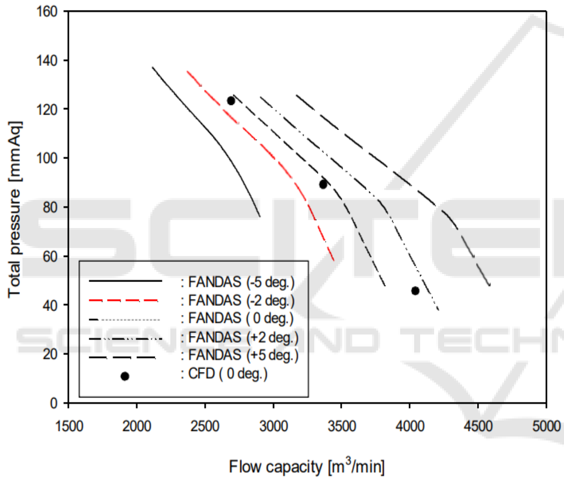

Figure 9: Total pressure curves of optimal fan.

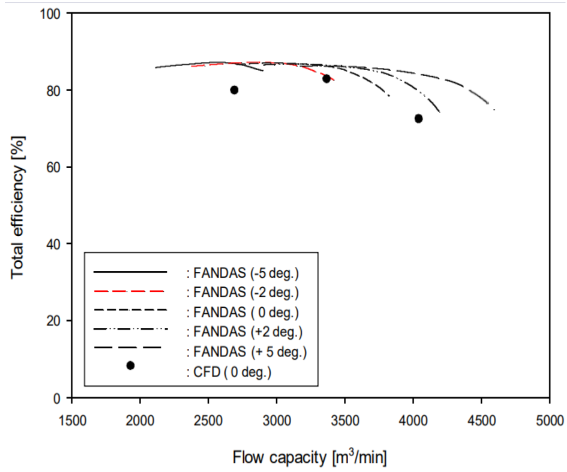

Figure 10: Total efficiency curves of optimal fan.

As the setting angle of optimal fan rotor blade is changed by adjusting the pitch angle from -5 to + 5 degree relative to the design setting angle (refer to Table 2), the operation range, the performance and the efficiency curves are moved into lower or higher flow domain so the optimal fan can be operated with high efficiency above 80% over wider flow capacity range between 2000 and 5000 m^3/min.

4 CONCLUSIONS

The present study provides a design optimization method of axial flow fan, which combines the FANDAS code for fan blade design and the PIAnO code for optimization. Based on the FANDAS code, a design optimization problem of axial flow fan is formulated and solved with multiple design variables and constraints by applying HMA algorithm of the PIAnO code. Through the optimization of fan rotor blade, fan efficiency is improved by 6.7 % relative to the initial design and the optimal fan can be operated with high efficiency over wide flow capacity range. Furthermore, under variable-pitch operation, the optimal fan can be operated with high efficiency over wider flow capacity range.

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