Optimal Design of a Variable-Pitch Axial Flow Fan by Applying Optimization Algorithm to Design, Through-Flow Analysis and CFD Simulation Methods

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Abstract: In order to develop a variable-pitch axial fan, an optimal three-dimensional fan blade is designed by using the 2-stage design optimization strategy to combine aerodynamic fan design program, CFD technique, and optimization algorithm. At the 1st stage of fan design optimization, the aerodynamic fan design program of this study is the FANDAS code where the chord length, setting angle, and camber angle of the fan blade are considered as design variables, and the performance, efficiency, and power of the fan are predicted by applying the through-flow analysis method to the designed fan. By applying a optimization algorithm to the FANDAS program, a three-dimensional fan blade shape is optimized and constructed for maximizing fan efficiency. At the 2nd stage of fan design optimization, CFD analysis method is also applied on the optimized fan from the first design optimization study, and additional design optimization for the blade setting angles is conducted by applying an optimization algorithm to the CFD model and simulation results. Furthermore the total pressure, efficiency, and power characteristic curves of the fan according to the variable-pitch operation conditions are calculated by applying the CFD technique to the final optimal fan model obtained through the 2-stage design optimization processes. From the CFD results on the characteristic curves of optimal fan, it is found that the optimal fan model of this study shows the highest efficiency of 91% at the design point, maintains high efficiency level of 80% in a wide flow range through variable-pitch operation.

1 INTRODUCTION

Axial flow fans are key flow components in various ventilation, air conditioning, and energy systems in industrial, commercial, and residential fields. A recent technical issue of axial fans is to improve fan performance and efficiency due to global climate change and carbon neutrality trends. Variable pitch axial flow fans have the advantage of maintaining high efficiency even in a wide flow range by adjusting the fan blade setting angle and reducing power by 15-20% compared to conventional fans (Wright, 2020). In a high efficiency axial fan design, since the air flow on the surface of the fan blade greatly affects the aerodynamic performance and efficiency of the fan, optimizing the geometric shape of 3D fan blade is a very important task of the fan designer (Kim, 2022). For this reason, in recent years, a lot of research has been conducted on optimizing fan blade design for high efficiency fan development (Angelini, 2017; Edward, 2021).

Therefore, in this paper, a new variable-pitch axial flow fan design is performed by applying the optimization algorithm to the fan blade design program and CFD calculation process to maximize fan efficiency. In this study, when fan design variables are given as inputs, a three-dimensional fan blade shape is constructed through a design program, and the total pressure, efficiency, and power of the fan are calculated as fan's key performance indices by

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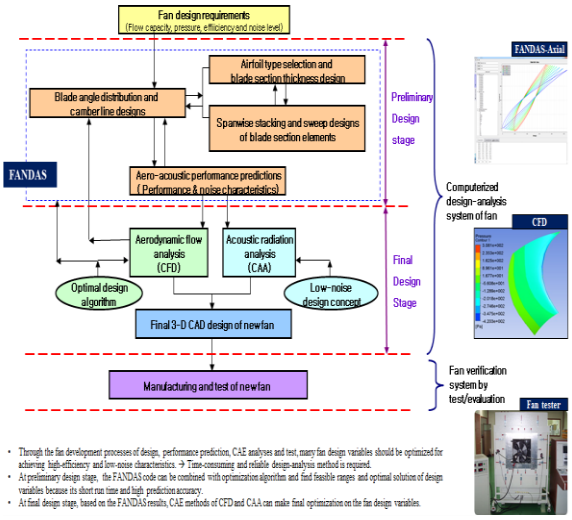
applying through-flow analysis or CFD method to the designed fan. And this design and analysis process is combined with an optimization algorithm to obtain optimal fan design. The optimal fan designed by this method is verified using CFD simulation, and the advantages of this optimal fan in terms of energy saving are identified by predicting the performance, efficiency, and power characteristics of the fan according to the variable pitch operation.

2 BACKGROUD ON FAN DESIGN

In Figure 1 showing general fan development procedure, final fan design can be obtained through a series of processes of geometry design, CFD analyses, manufacturing and testing. Traditionally, 3D fan blade shape has been made by design programs based on aerodynamic theories (e.g., the FANDAS code), and CFD techniques have been used to verify the flow and performance of such designed fans. And most fan design optimizations have also been performed using design programs. However, because of recent remarkable advances in optimization techniques and computing power, fan design optimization problems can be handled not only with design programs but also with CFD simulation methods, even though there are many fan design variables. For this reason, the present study proposes two-stage design optimization strategy for the fan development procedure of Figure 1, where optimization algorithm is sequentially combined with design program (the FANDAS code, 1st stage) and CFD technique (the ANSYS CFX code, 2nd stage).



- Through the fan development processes of design, performance prediction, CAE analyses and test, many fan design variables should be optimized for achieving high-efficiency and low-noise characteristics. → Time-consuming and reliable design-analysis method is required.
- At preliminary design stage, the FANDAS code can be combined with optimization algorithm and find feasible ranges and optimal solution of design variables because its short run time and high prediction accuracy.
- At final design stage, based on the FANDAS results, CAE methods of CFD and CAA can make final optimization on the fan design variables.

Figure 1: General fan development procedure.

3 FAN DESIGN PROGRAM WITH THE PERFORMANCE PREDICTION BY THROUGH-FLOW ANALYSIS

The present study employs a fan blade design program which has been developed and verified in the university laboratory of the present authors (FANDAS, 2023). In this study, chord length, stagger angle and camber angle are considered as design variables to determine blade section as shown in Figure 2. The camber line of the blade section is determined by using single circular arc to meet given camber angle, and NACA 6308 airfoil thickness distribution is added onto the camber line to construct blade element profile (refer to Figure 2). Once blade section elements are determined from the three design variables, 3D fan blade geometry is constructed by the stacking of the blade section elements along blade span height from hub to tip.

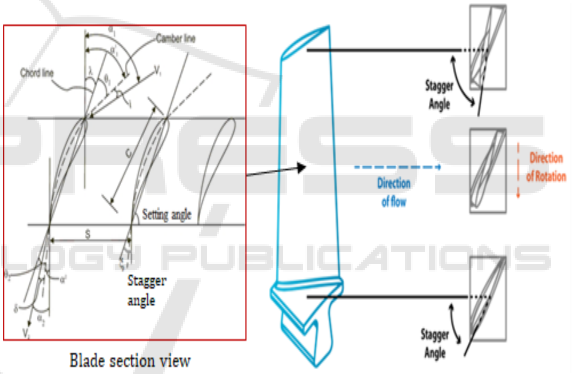


Figure 2: Main fan blade design parameters.

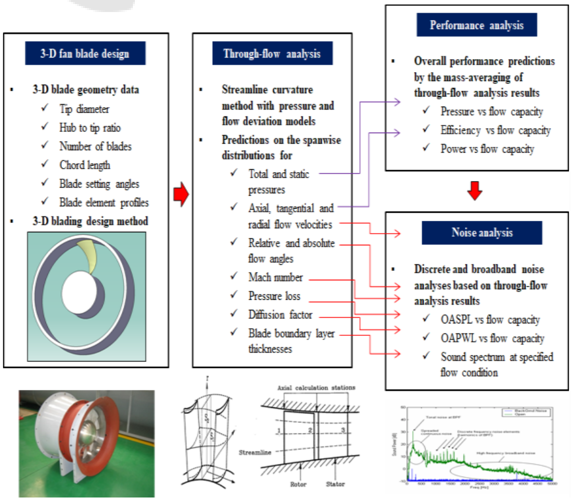


Figure 3: Through-flow analysis procedure.

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After 3D fan blade shape is determined, the design program can also predict the performance, power and efficiency of designed fan by a through-flow analysis method. Figure 3 shows the performance prediction procedure of the present fan design program. The FANDAS code can 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 flow deviation and total pressure loss models (Lee, 2021).

In this study, the through-flow analysis method of the FANDAS code is applied to a variable pitch axial flow fan of Figure 4, which is designed with camber and stagger angle distributions in Figure 5. Here setting angle is defined as 90º – stagger angle. As shown in Figure 6, the present performance predictions are favorably matched with the test results (van der Spuy, 1997/2002) at different fan-blade pitch angles when the setting angle of blade hub is set to 25, 35 or 45 deg.

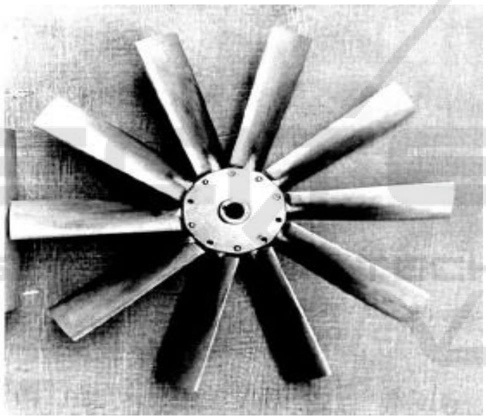

Figure 4: Rotor blades of a variable pitch fan.

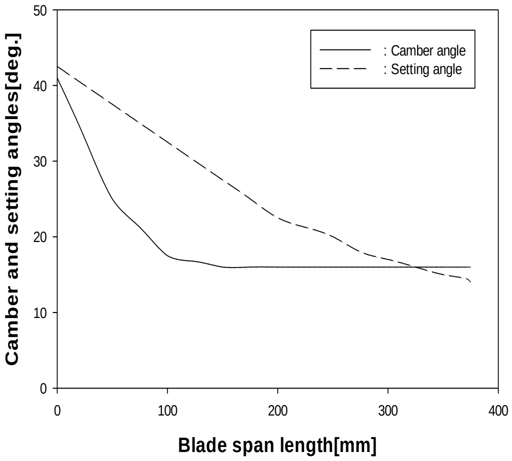

Figure 5: Camber and setting angle distributions.

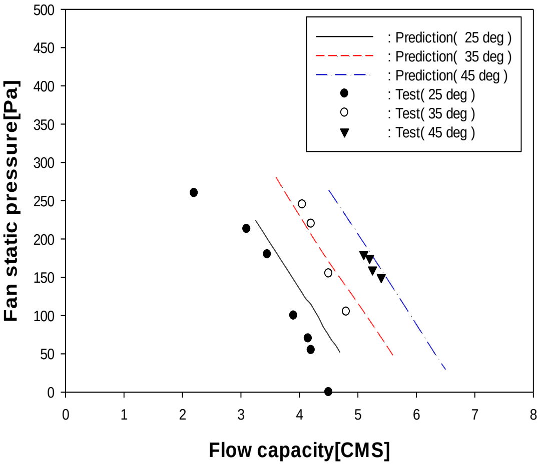

Figure 6: Performance curves of variable pitch fan.

4 2-STAGE FAN DESIGN OPTIMIZATION STUDY

4.1 1st Stage: Optimal Fan Design Using Through-Flow Analysis Method

In the 1st stage design optimization, objective function is defined as the total pressure efficiency of fan, which is calculated by the through flow analysis method of the design program, the FANDAS code. Design variables of this study are the camber angle (θ_c), the setting angle (ξ) and the chord length (c) of fan impeller blade (refert to Figure 7), so optimization problem is formulated as

$$\text{Optimize } \theta_c(\mathrm{r}), \xi(\mathrm{r}) \text{ and } \mathrm{c}(\mathrm{r}) \text{ to maximize } \eta \\ \text{with design constraints in Table 1}$$

where the camber angle, the stagger angle and the chord length are defined as design variables at three blade span locations of hub (0% span), mid-span (50% span) and tip (100% span) in Figure 8, and their functions of spanwise direction, r, are constructed in the form of parabolic curves using the defined design variables at those three locations.

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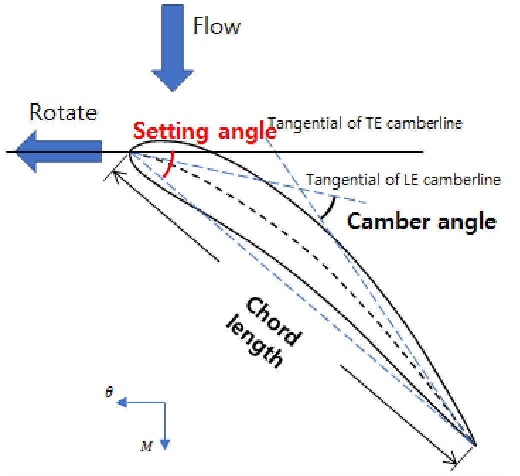

Figure 7: Definitions of camber, setting angles and chord length of impeller blade.

Table 1: Design constraints for design optimization.

Design constraints	Fixed design parameters
$Q = 5{,}400\ m^3/min$ $2{,}000 < p_T < 2{,}400\ Pa$ Power < 300 kW $0 < \theta_c < 90$ deg. $0 < \xi < 90$ deg. $0.5 < \dfrac{c}{2\pi r/Z_b} < 2.5$	RPM = 1200 Tip diameter =1,985[mm] Hub/tip ratio = 0.564 No. of blades (Z_b) = 12 Tip clearance = 5 [mm]

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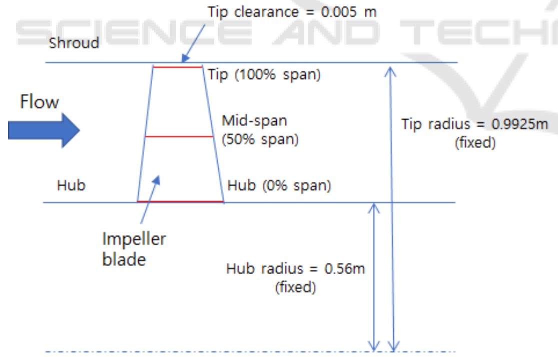

Figure 8: Meridional view of fan rotor blade.

The determined camber, stagger angles and chord lengths are used as input data of the through-flow analysis method for the efficiency prediction of the designed fan model. Optimization algorithm used in this study is Hybrid Metaheuristic Algorithm (PIDOTEC, 2021), which is coupled with the design program with through-flow analysis.

Optimal design variables are obtained and shown in Figures 9-11 after several iterative calculations are carried out. Comparing the initial and the 1st optimal results, the optimal camber angles at hub and tip are somewhat higher than the initial ones while the optimal setting angle at hub is higher than the initial one. The optimal chord lengths at mid-span and tip is smaller than the initial ones and its magnitude decreases from hub to tip. It is noted that initial design is made by free vortex method (McKenzie: 2017). The efficiency of optimal fan model, 87.2% is improved by 3.6 % when compared with the initial design, 83.6%.

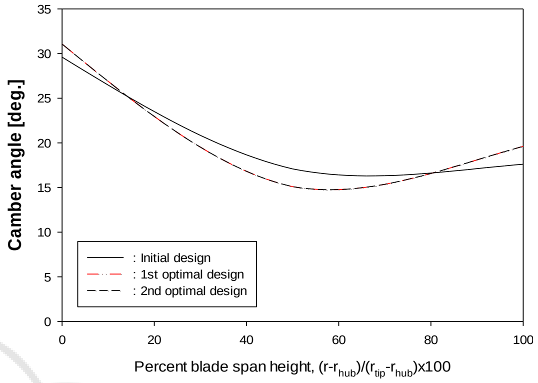

Figure 9: Camber angle distributions of fan blade.

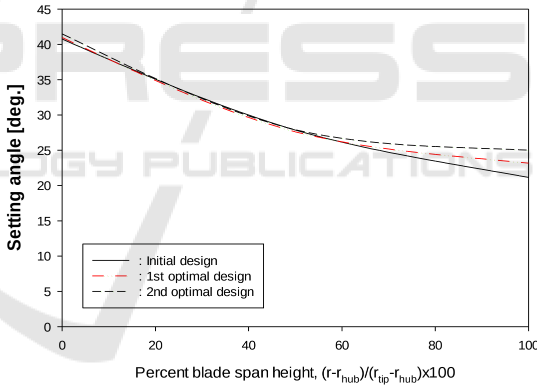

Figure 10: Setting angle distributions of fan blade.

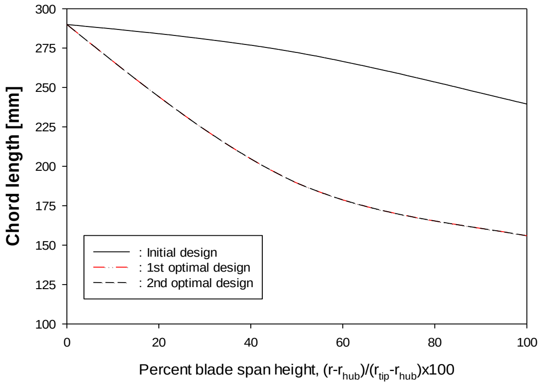

Figure 11: Chord length distributions of fan blade.

4.2 2nd Stage: Optimal Fan Design Using CFD Method

In the 2nd stgae design optimization, optimization algorithm is applied to CFD modelling and simulation method for further efficiency improvement from the 1st stage optimal design model. Since the through-flow analysis method used in the 1st stage optimal design is a one-dimensional method, it is impossible to predict the three-dimensional flow effects and pressure losses such due to spanwise mixing, so the application of the CFD method can be considered to predict these three-dimensional flow effects and pressure losses and reflect them in the fan design. However, since numerical calculations by the CFD method require more time and effort than through flow analysis, it is not suitable for optimization handling many design variables, so only three setting angles out of the nine design variables considered in the 1st stage optimization study are considered as design variables in this study, and the remaining camber angle and cord length are fixed as the optimal design result in the 1st step. Objective function is also defined as the total pressure efficiency of fan, which is determined by CFD calculations of the ANSYS CFX code.

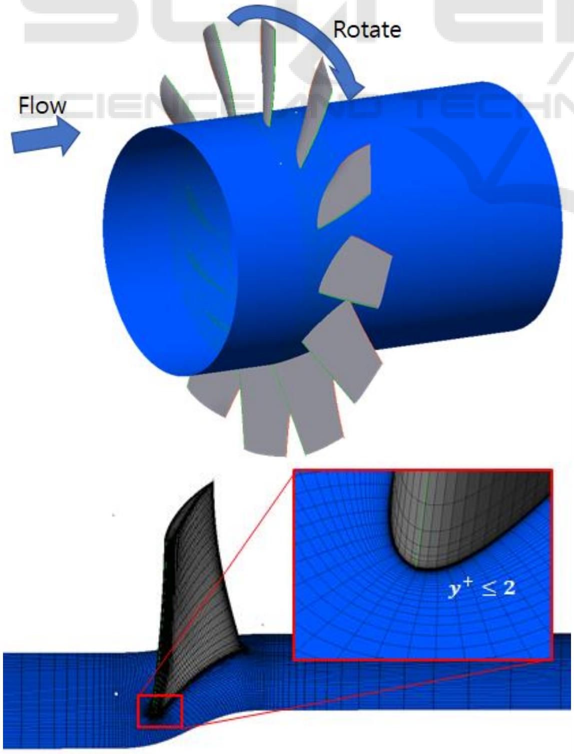

Figure 12: Mesh system of rotating fan blades.

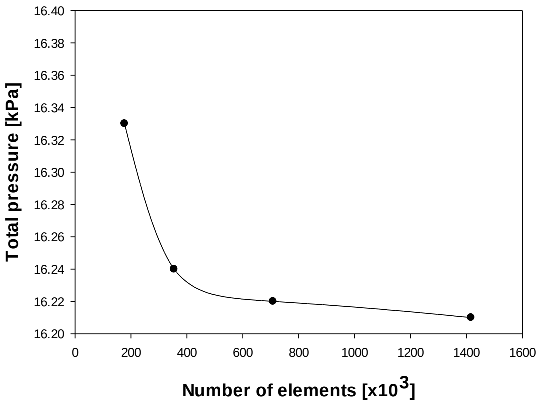

Figure 13: Grid dependency test of mesh system.

Structured mesh systems on the flow domain between nearby fan blades are constructed by uing the Turbo grid program (refer to Figure 12). Mesh quality and grid dependency tests are conducted on mesh systems with different number of elements, and the mesh system with 708x10^3 elements shows very good grid convergence index of 4.42x10^{-4} on total pressure predcition, so is used in this optimization study (refer to Figure 13).

Through the 2nd design optimization on setting angles with CFD simulations, the optimal setting angle distribution is obtained, and the shape change of the 3D blade is shown in Figure 14. The setting angle near the tip is somewhat larger than that of the 1st optimal design and is increasing by up to 2 degrees. The fan efficiency by the 2nd optimal design is calculated to be 91.4%, which is 4.2% improvement compared to the 1st optimization result. Figure 15 compares the efficiencies of the initial, the 1st and the 2nd optimal design models, and shows 7.8% efficiency improvement through 2 stage design optimization processes.

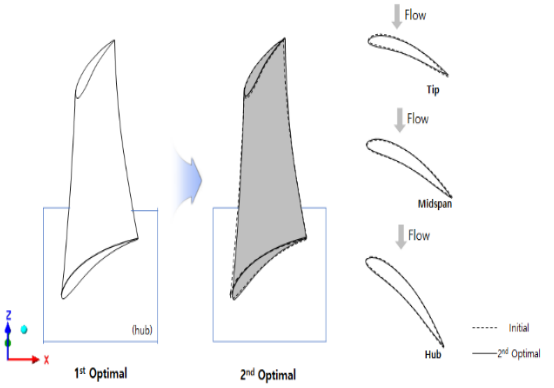

Figure 14: 3-D Fan blade shapes of 1st and 2nd optimal models.

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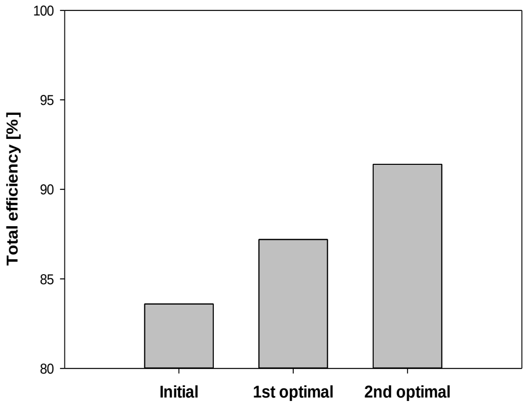

Figure 15: Fan efficiency comparison.

5 CFD ANALYSIS ON THE OPTIMAL FAN MODEL UNDER VARIABLE-PITCH OPERATION

The changes of the total pressure, efficiency and power of the optimal fan model according to the flow rate are calculated using the CFD method while change of the setting angle relative the optimal one (pitch angle) is from -10 to +10 degree. The optimal fan model is considered as the case where a cambered plate type guide vane is installed behind the impeller blade obtained through this optimization study. For reference, in this study, the manufacturing of the optimal design model is in progress, so the CFD results can’t be compared with the test results. As shown in the efficiency curve of Figure 16, it can be seen that the efficiency can be maintained as high as 80% or more even under flow conditions that are less or more than the design flow rate by adjusting the pitch angle. From the total pressure curves of Figure 17, when the pitch angle is fixed as 0 degree, surge occurs at a small flow rate, but by reducing the pitch angle, surge is avoided and stable operation is possible. Figure 18 shows that the fan can be operated with relatively low power even in small flow conditions through the change of the pitch angle. In addition, when the flow rate increases, increasing the pitch angle improves efficiency and reduces power (refer to Figures 16 and 18).

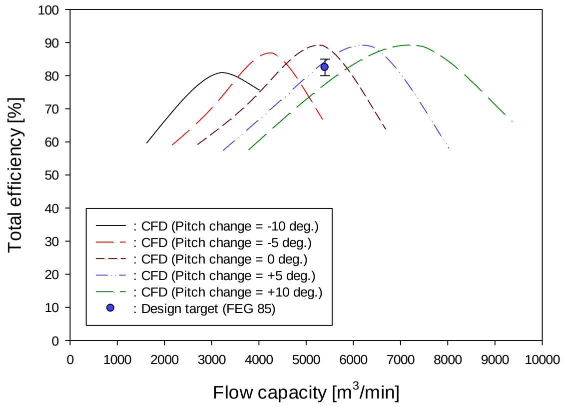

Figure 16: Efficiency curves of the optimal fan model under variable-pitch operation.

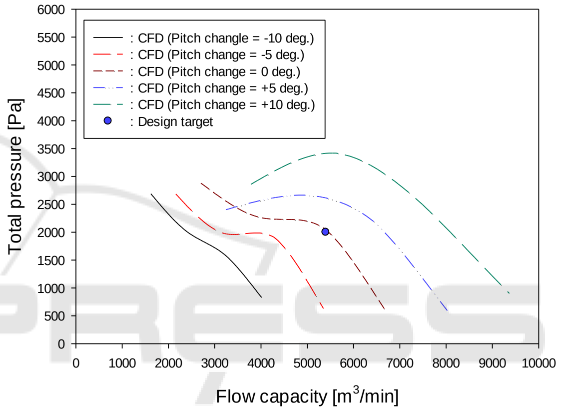

Figure 17: Total pressure curves of the optimal fan model under variable-pitch operation.

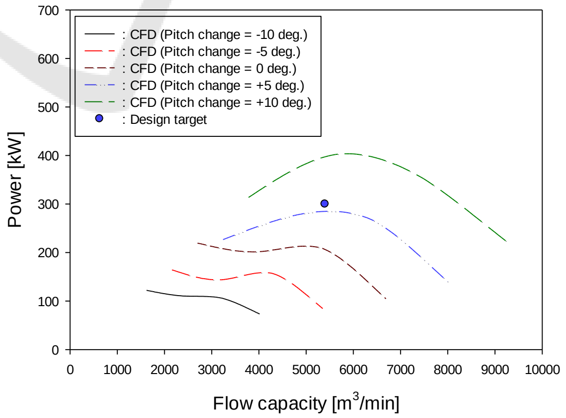

Figure 18: Power curves of the optimal fan model under variable-pitch operation.

6 CONCLUSIONS

The present study proposes a design optimization strategy and procedure of axial flow fan, where optimization algorithm is applied to fan design models with the through-flow analysis method of design program at the 1st stage and CFD method at the 2nd stage. Design optimization problems of axial flow fan are formulated and solved with multiple design variables and constraints. Through the 1st and the 2nd stage des+ign optimizations of fan rotor blade, fan efficiency is improved by 3.6 % and 4.2% respectively. Furthermore, under variable-pitch operation, the final optimal fan is shown to be operated with high efficiency over wider flow capacity range.

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