Design Optimization Method and Application of High-Efficiency and Variable-Pitch Axial Flow Fan

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Abstract. This paper describes servo motor–driven variable-pitch axial flow fan, and its optimal design method, process and application results for improving the efficiency of the variable-pitch fan. The design program for constructing axial flow fan geometry is developed by combining fan blade section design and through-flow performance prediction methods. The optimization technique of this study is Hybrid Metaheuristic Algorithm which is combined with the design program to find optimal design values of blade setting angles, camber angles and chord lengths, and then to maximize the fan efficiency. The axial flow fan obtained in this optimization study shows 6.7% higher design-point efficiency than the initial design and wide operation range with high efficiency by changing the pitch-angle of the fan rotor blade.

1 Introduction

Axial flow fans are important machines used in many applications, and the recent global climate change and carbon neutrality issues have further required the development of high-efficiency fans to reduce the power required. One way to reduce fan power is a variable pitch fan mechanism that secures high fan efficiency over a wide range of operations by adjusting and controlling the fan blade setting angle by means of a hydraulic or servo motor mechanism. Furthermore, since the three-dimensional fan blade shape of variable pitch axial fans greatly affects fan efficiency, many studies have been conducted on the blade design and performance analysis of highly efficient axial fans over a wide range of flow capacities. McKenzie [1] presented a method for designing rotor blade shapes for variable pitch axial fans using blade robustness and correlations expressed by the setting angle. Wallis [2] proposed a method of designing a blade of a variable blade axial fan by using the correlation between the flow angle and the blade cross-sectional lift coefficient. A typical applied fan development study [3] has found that the blade angle determination of blade sections along the blade span is a very important design problem for variable pitch fans, applying various design methods and verifying their effectiveness through measurement and CFD modelling. Spuy and Backstrom [4] optimized the blade angle distribution to minimize kinetic energy at the outlet of an axial fan with a variable pitch rotor. For the automotive cooling axial fan

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design, Lee [5] defined the camber angle, setting angle, and chord length of the fan blade section as design variables and compared the performance characteristics of the fan according to different fan blade design methods.

Therefore, in this study, variable-pitch operation mechanism for axial flow fan is explained and the 3-D fan blade shape design optimization method, process and application results are provided. The comparisons between the optimal fan with variable-pitch mechanism and the existing fan show remarkable flow capacity range expansion, efficiency improvement and electric power reduction through high-efficiency and variable-pitch fan operation.

2 Blade design parameters of variable-pitch axial flow fan

An axial fan is an electric machine that increases pressure by introducing air by rotating the blade by a motor, and the blade has a complex three-dimensional shape as shown in Fig. 1. In addition, the air passing through these blades has the characteristic that the pressure and efficiency change significantly depending on the flow rate, which has the disadvantage of a relatively small flow rate range. For this reason, the development of a high-efficiency fan is required through the optimal shape design of the blade, and research and development are being attempted to secure a wide flow rate range through variable operation of the blade pitch angle, β (or hub setting angle). In general, most of the pitch angle adjustments of fan blades are made by hydraulic pressure, but the disadvantages of the hydraulic method include failure of the hydraulic pump and hydraulic cylinder, environmental pollution due to leakage in the hydraulic pipe system, damage to equipment, and slow response characteristics. Therefore, this study adopted an electrical servo motor method to overcome the disadvantages of this hydraulic system (see Fig. 1)

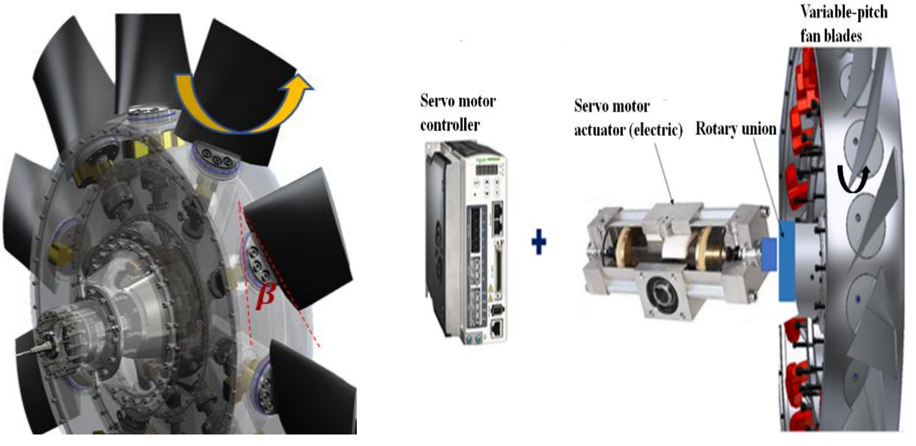

Fig. 1. Servo-motor driven variable-pitch axial flow fan

As shown in Fig. 2, 3D fan blade shape is constructed by designing 2-D blade sections and stacking the section elements along blade span height and the main design parameters are setting angle, camber angle and chord length of blade section. Especially the setting angle and camber angle is the most important design parameters to determine fan flow capacity, pressure and efficiency. For this reason, this study selects the setting angles, camber angles and chord lengths at hub, mid-span and tip locations along blade span.

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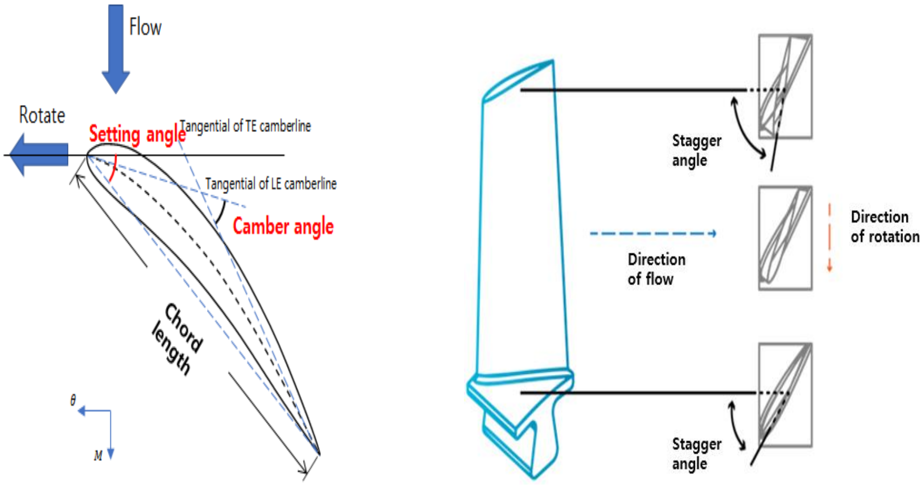


Fig. 2. Fan blade section design parameters and 3-D fan blade geometry

3 Axial flow fan design program

In this study, a design program, FANDAS, is developed and used to design the blade shape and predict the performance of variable pitch axial fans. The FANDAS program has been developed and verified by the authors, and can make the 3D fan blade shape design and the performance prediction by through flow analysis method. The performance prediction method by through flow analysis used in the FANDAS program is described in detail in Reference [6]. The design reliability and prediction accuracy of the FANDAS program are verified by comparing the internal flow field and performance prediction results of the axial fan with the measurement results [4,7] as shown in Figure 3,4,5. From the comparison results, it can be seen that the FANDAS program can be suitably used for design and efficiency prediction in design optimization of variable pitch axial fans.

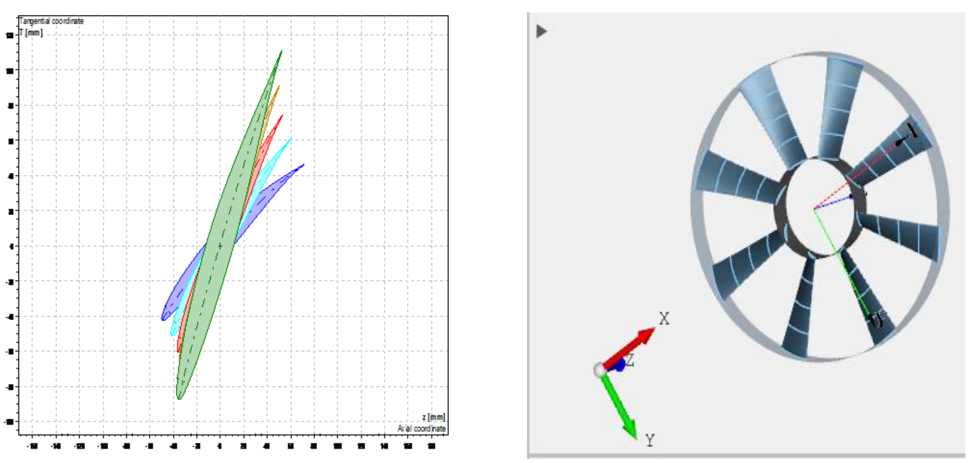


Fig. 3. 2-D fan blade section and 3-D fan blade geometry designs

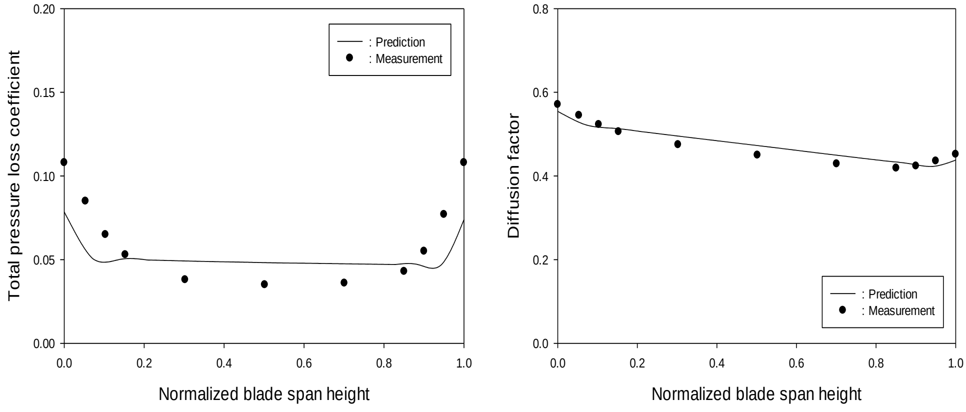


Fig. 4. Spanwise distributions of pressure loss coefficient and diffusion factor

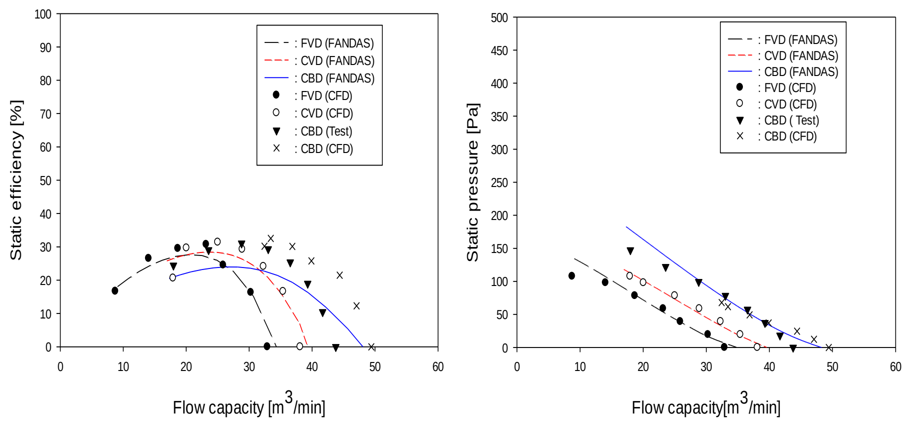


Fig. 5. Overall pressure and efficiency curves of fans

4 Design optimization of variable-pitch axial flow fan

In this optimization study, the FANDAS program is used as a tool for fan blade design, performance and efficiency predictions. In addition, the FANDAS program is integrated with the hybrid metaheuristic algorithm as an optimization technique [8]. Chord lengths, camber angles and setting angles at hub (blade span 0%), mid-span (blade span 50%), and tip (blade span 100%) locations are treated as design variables, and mathematical formulations with the design variables and several design constraints are performed for the fan efficiency maximization problem. The objective function of this optimization problem is defined as the total pressure fan efficiency (η_T) at the design point 3300m^3/min, which is a function of camber angles, setting angles, and chord lengths at the aforementioned hub, mid-span and tip locations, and the design variables are optimized by the hybrid metaheuristic algorithm based on the results predicted by the FANDAS program. As an optimization problem with constraints, this study used 11 constraints including the allowable range of total pressure and the design ranges for the camber angle, setting angle, and chord length. In this study, a meta model is created using the FANDAS code, and the prediction error between the meta model and the FANDAS code is 0.011%, so the calculation of the meta model for optimization proceeds accurately and quickly. The time required for the design and performance prediction of a single fan model by the meta model is only a few seconds.

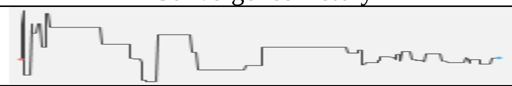
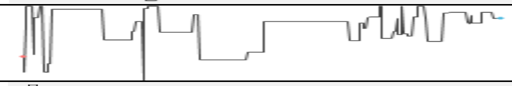
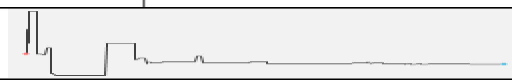
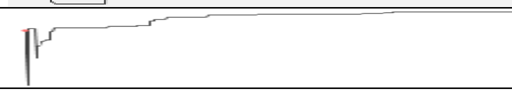
Design variable & objective function	Convergence history
Setting angle (tip)	
Camber angle (tip)	
Chord length (tip)	
Total efficiency (η_T)	

Fig. 6. Convergence histories of design variables and objective function

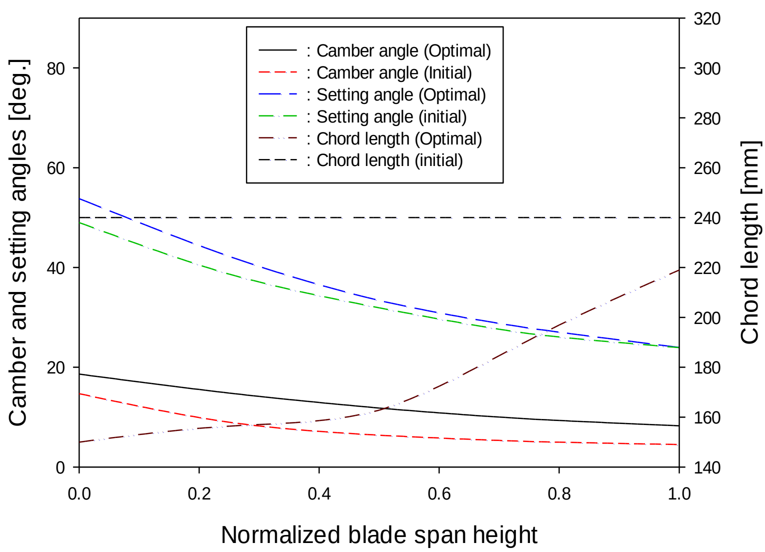


Fig. 7. Optimal fan blade angles and chord length

After several iterative computations for reaching to optimum design point (refer to Fig. 6), optimal design variables and the maximum fan efficiency are obtained and compared with the initial design (refer to Fig. 7). The optimal camber angle appears larger than the initial design value along the entire blade span, while the optimal setting angle at the hub (or pitch angle) has fewer values than the initial design. The setting angle is defined as the 90-stagger angle [deg.]. The optimal chord length is smaller than the initial design with constant chord length and increases from the hub to the tip. The design point efficiency of the optimal fan appears to be 85.8%, an improvement of 6.7%p compared to the initial design value. The optimal fan blade shape has been fabricated and shown in Fig. 8.

Fig. 8. Optimal fan blade geometry

In this study, CFD technique is also used to check optimal fan design and verify fan performance. The CFD model is constructed with structured mesh system in flow domain of optimal fan rotor and outlet guide vane. Numerical computations are conducted by the ANYSYS CFX code with Frozen rotor scheme or the SIMERCIS MP code with MRF scheme for the interface between rotors and outlet guide vanes, and the ANSYS CFX computation employs standard k-ω SST model and the SIMERICS MP code uses standard k-ε model for turbulent flow inside fan blades [9,10]. The fan performance calculation results by the standard k-ε model of the SIMERICS MP code and the k-ω SST model of the ANSYS CFX code are almost identical. Fig. 9 shows mesh system used in this CFD modelling and the flow domain is defined around optimal fan rotor blade and outlet guide vane with infinite axis.

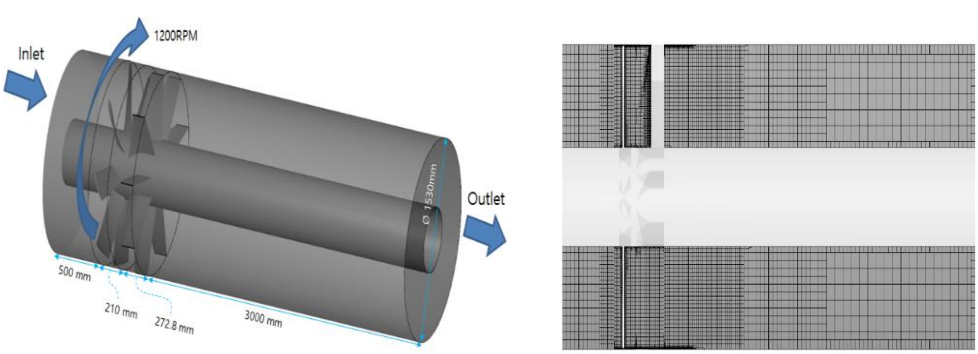


Fig. 9. Mesh system for optimal fan modelling and simulation

Fig. 10 compares the FANDAS prediction, the CFD prediction and the test results. The FANDAS design results of optimal fan are matched well with the CFD and the test results. The difference between the FANDAS and the test results can be explained by that actual fan tests are conducted with finite axis, hub cap and tail cone so the test results are decreased by the pressure losses at hub cap and tail cone when compared with the FANDAS design with infinite axis. As can be seen in Fig. 11, when pitch angle is fixed as the optimal design value (reference case), the design point fan efficiency predicted by the FANDAS code is 85.8%, which is significantly larger than the initial value, 79.1%. The total pressure efficiency of the optimal fan model is also maintained above 80% over the entire operating flow range by changing the pitch angle.

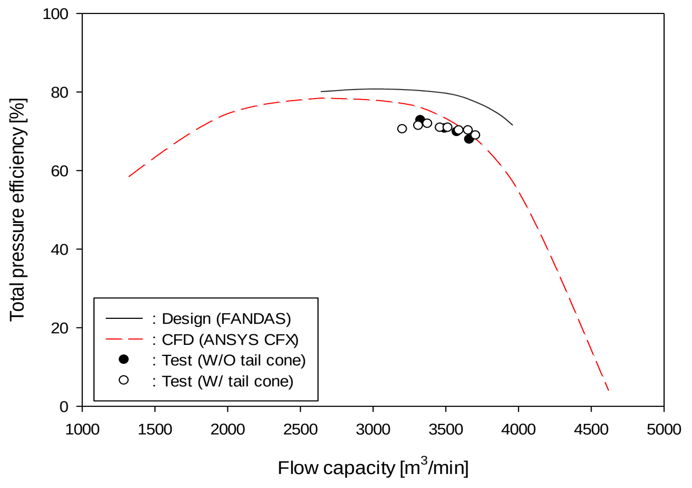


Fig. 10. Efficiency curve of optimal fan at fixed pitch-angle

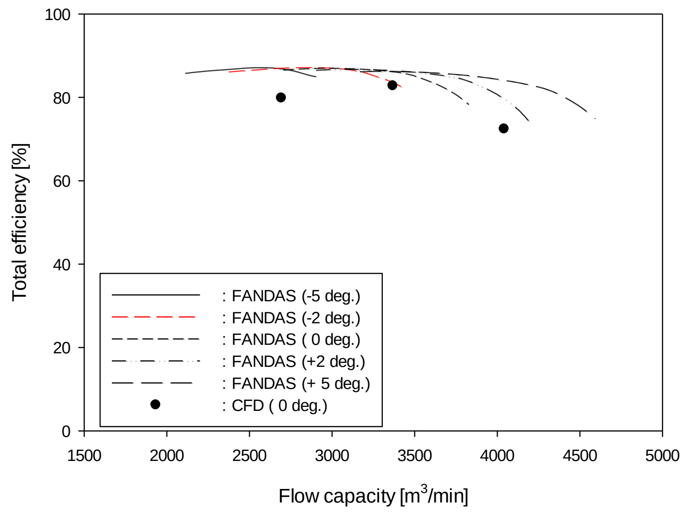


Fig. 11. Efficiency curves of optimal fan due to the changes of pitch angle

5 Conclusions

This study presents the optimal design method for axial flow fans to maximize efficiency and reduce power consumption. In this study, the fan design program is developed and combined with the optimization algorithm. The optimal fan design is verified by CFD simulation and actual fan testing. By using the optimal design fan blade and adjusting the pitch angle of the blade, it increases the design point efficiency of the optimal fan by 6.7% compared to the initial design, increases the flow capacity range more than that of the fixed pitch angle blade fan, and maintains the fan efficiency by more than 80% under variable pitch operation conditions.

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