Conference on Modelling Fluid Flow (CMFF'25)
The 19th International Conference on Fluid Flow Technologies
Budapest, Hungary, August 26 -August 29, 2025

MULTI-OBJECTIVE DESIGN OPTIMIZATION OF A VARIABLE-PITCH AXIAL FLOW FAN BY USING CFD-BASED META-MODEL

Chan LEE[1], Hyung Jin LEE[2], Sang Yeol LEE[3] , Sang Ho YANG[3]

[1] Corresponding Author. Department of Mechanical Engineering, Faculty of Mechanical Engineering, University of Suwon. Hwaseong, South Korea, Tel.: +82 31 220 2219, E-mail: clee@suwon.ac.kr
[2] PIDOTEC, Beobwon-ro, Songpa-gu, Seoul, South Korea
[3] Research Lab., Samwon E&B, Siheung, South Korea

ABSTRACT

This study defines the design-point efficiency and the standard deviation between the maximum efficiencies under variable-pitch operating conditions as multi-objective functions for a variable-pitch axial flow fan rotor blade. A CFD modeling-based meta-model is developed and used as the simulation engine for this optimization. The CFD model for the variable-pitch fan rotor blade utilizes Reynolds-stress averaged Navier-Stokes equation solver and employed a fine mesh system with $y^+<2$. The meta-model is constructed based on CFD simulation results obtained by changing the pitch angles at the hub, mid-span, and tip of the fan rotor blade, which serve as the design variables. Using the results of the meta-model, a Pareto front is derived, enabling the identification of an optimal design that maximizes design-point efficiency while minimizing the efficiency standard deviation. The CFD-predicted total pressure, efficiency, and power characteristics of the optimally designed variable-pitch fan rotor blade are compared with those of the initial design. From the comparison results, the design-point efficiency of the optimal fan blade rotor is improved by 3.7 percentage points compared to the initial design, and the efficiency standard deviation is reduced to 0.76%.

Keywords: Axial flow fan, CFD, Fan performance, Optimization, Variable-pitch fan operation

NOMENCLATURE

β	[*deg.*]	blade setting angle
θ	[deg.]	tangential coordinate
η	[-]	efficiency
P_T	[*Pa*]	total pressure
Q	[m^3/s]	volume flow rate
y+	[-]	non-dimensional thickness

1. INTRODUCTION

Recent technical challenge for axial flow fans has been to improve fan performance and efficiency in response to global climate change and the trend toward carbon neutrality. Variable pitch axial flow fans offer the advantage of maintaining high efficiency across a wide range of airflow by adjusting the angle of the fan blades, resulting in a 15-20% reduction in power consumption compared to conventional fans[1]. In high-efficiency axial flow fan design, the airflow over the fan blade surface significantly impacts the fan's aerodynamic performance and efficiency, making the optimization of the 3D fan blade geometry a critical task for fan designers[2]. For this reason, there has been extensive research into optimizing fan blade designs for the development of high-efficiency fans[3,4].

Therefore, this paper conducts a new variable pitch axial flow fan design to maximize fan efficiency by applying optimization algorithms to the meta-model based on CFD (Computational Fluid Dynamics) calculation results. In this study, fan design variables are input, and a 3D fan blade shape is constructed through the design program. The designed fan undergoes CFD modelling to calculate key performance indicators such as total pressure, efficiency, and power. This design and analysis process constructs a meta-model which can be combined with the optimization algorithm to obtain the optimal fan design. The optimal fan designed by this method is verified through CFD simulation, and the performance, efficiency, and power characteristics of the fan are predicted based on variable pitch operation to evaluate the energy-saving benefits of this optimal fan.

2. DESIGN AND CFD MODELLING-BASED META-MODEL OF AXIAL FLOW FAN

This study uses the fan blade design program, the FANDAS[5], which was developed and validated in the author's university laboratory. In this study, design variables such as setting angle and camber angle are considered to determine the blade cross-section, as shown in Fig. 1. Once the blade cross-section elements are determined from the camber and setting angles, the blade cross-section elements are stacked along the blade span height from hub to tip to form the 3D fan blade geometry.

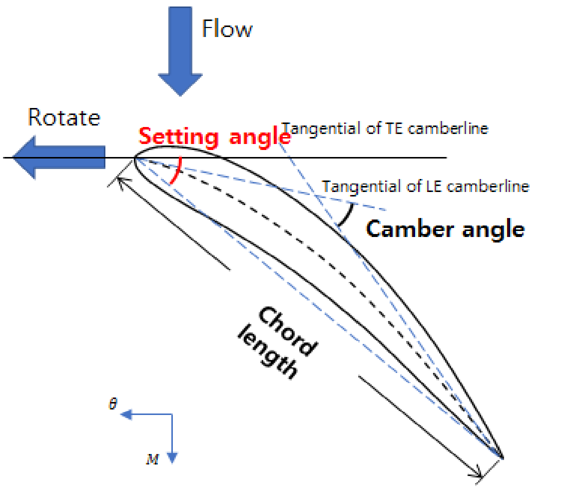

Fig. 1 Camber and setting angles of impeller blade

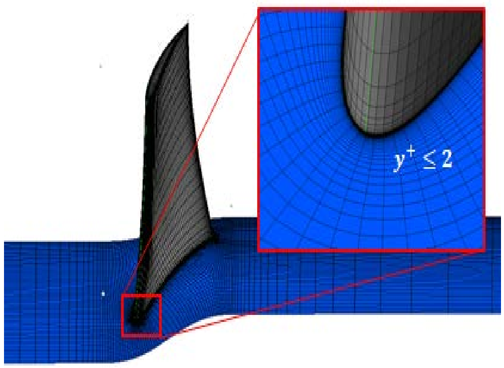

Fig.2 Mesh system on fan impeller blade surface

CFD modeling is performed on fan impeller blades designed by changing the camber angle and setting angle. The ANSYS CFX code[6] is used for the CFD modeling, steady-state RANS (Reynolds-stress Averaged Navier-Stokes equation) solver is used as a numerical analysis method for incompressible and viscous flow, and a k-ω SST model is also used as a turbulence model. For precise calculation of the viscous boundary layer on the impeller blade surface, the wall mesh size is set to y+ < 2 (refer to Fig. 2). The structured mesh is generated using the TurboGrid.The mesh consists of a total of 576,206 cells, with 463,016 cells allocated to the impeller region, where the main viscous flow is generated. The interface between the impeller and stator is treated using the Frozen Rotor approach, aligned with the impeller blade. For the boundary surfaces with repeating conditions, a Rotational Periodic Condition is applied.

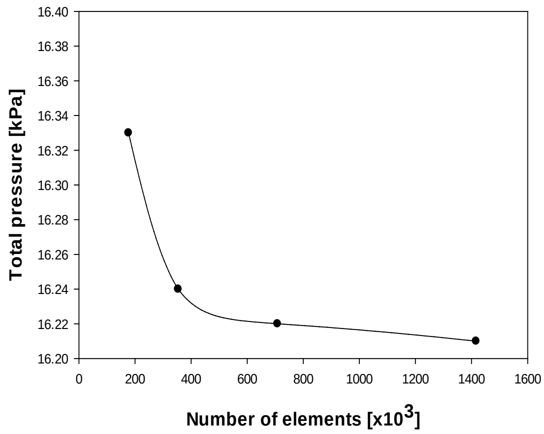

Fig. 3 Grid dependency test of mesh system

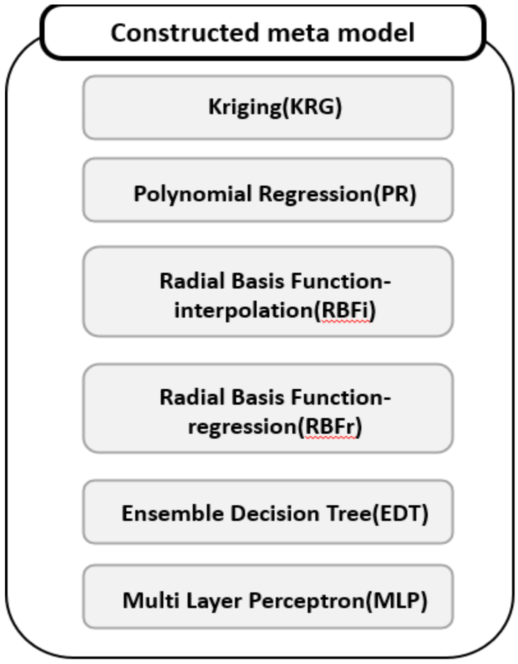

Fig. 4 Meta-model construction processes

In addition, as shown in Fig. 3, the mesh system with the most efficient and highest calculation accuracy is selected through the grid dependency test. Based on the fan performance and efficiency analysis results calculated according to the change in the camber angle and setting angle, a meta-model for fan total pressure, efficiency, and power prediction is constructed. For the meta-model construction, various mathematical techniques [7,8,9] are combined, as shown in Fig. 4. There are two main methods for obtaining data to construct a meta model:

using only pre-existing data and acquiring new data specifically for model construction. The former approach may suffer from data bias or insufficient data volume, but it does not require additional resources, making it a viable option when acquiring new data is difficult. The latter method allows for more balanced data distribution to mitigate potential bias and can produce accurate predictive models even with relatively small datasets; however, it demands additional resources and is typically employed when a new design is introduced or when high prediction accuracy is required. In this study, the former method is chosen due to the substantial resources required for each individual experiment. To mitigate the prediction error caused by the limited amount of available data, six different predictive models are constructed using the same dataset: Kriging (KRG), Radial Basis Function interpolation (RBFi), Polynomial Regression (PR), Radial Basis Function regression (RBFr), Multi-Layer Perceptron (MLP), and Ensemble Decision Tree (EDT). Kriging combines a global model and residuals to accurately pass through the experimental points. RBFi determines performance values by assigning weights to the training data around the prediction point; if the model passes exactly through the experimental points, it is considered RBFi, otherwise it is referred to as RBFr. Polynomial regression is a traditional method that assumes a polynomial form of the data and estimates the coefficients using the least squares method. MLP is a type of artificial neural network with multiple hidden layers that receives inputs through several neurons, applies weights and activation functions, and outputs the prediction result. Lastly, EDT employs a random forest algorithm to train multiple decision trees and combines their outputs for prediction.

Comparing the prediction results by meta-model with the CFD calculation results, the prediction differences are within 0.2%p, indicating that the meta-model shows very accurate prediction results, and furthermore, it is suitable for using the meta-model as a simulation engine for the fan design optimization process for maximizing efficiency.

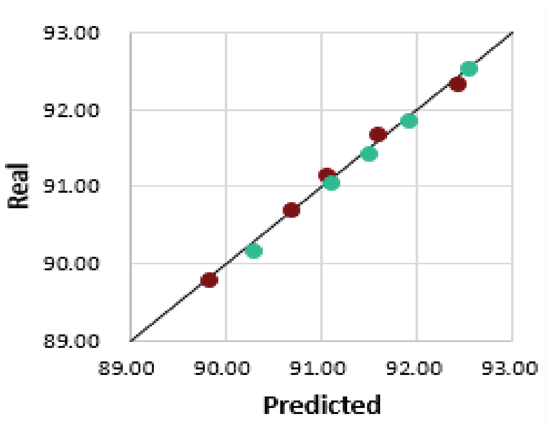

Fig.5 Comparisons between the 3-D CFD simulation (real) and the meta model (predicted)

3. MULTI-OBJECTIVE DESIGN OPTIMIZATION OF A VARIABLE-PITCH FAN

Before performing the optimal design by combining the aforementioned meta-model and an optimization algorithm, it is necessary to define the multi-objective function of the variable-pitch axial fan in this study. Fig. 6 shows the change in the performance and efficiency of the fan under variable-pitch operation conditions. As can be seen in Fig. 6, the variable-pitch axial fan is important in efficiency at the design point, but also requires the characteristic that the efficiency does not decrease rapidly under variable pitch conditions (change in setting angle, β). Therefore, this study defines the efficiency of the design point and the deviation between the maximum efficiencies under different variable pitch conditions as the objective functions of the optimization problem (refer to equations 1 and 2), and optimization (maximization of design point efficiency and minimization of efficiency deviation) of these two objective functions is performed.

$$\eta_{des} = \frac{\Delta P_T Q}{Torque \times Anqular\ frequency} \qquad (1)$$

$$\Delta\eta = \eta_{peak,\beta} - \eta_{des} \qquad (2)$$

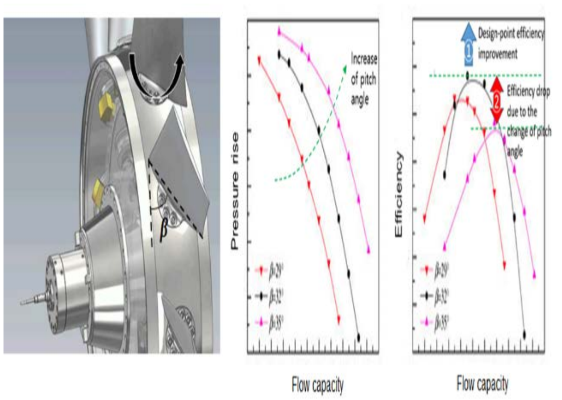

Fig. 6 Performance and efficiency characteristics of variable-pitch axial flow fan

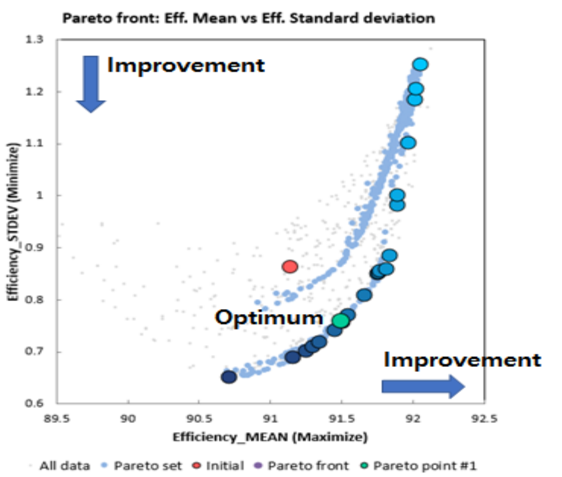

Fig. 7 Pareto front for optimal axial flow fan design

For the design optimization, the camber angles and setting angles are considered as design variables at the impeller blade hub, mid-span and tip locations, so six design variables are dealt with in this study. Table 1 presents the design conditions used in this study, and the variation in blade setting angle (or pitch angle) ranges from -5 degrees to +5 degrees.

Table 1 Design specifications of axial flow fan

Q [m^3/s]	P_T [Pa]	RPM	Power[kW]
90	2000	1200	200

The Pareto front is created by combining the previously constructed meta-model and the optimization algorithm. Fig. 7 shows the Pareto front for the design point efficiency and efficiency deviation, and a region in which the improvement of the design point efficiency and the reduction of the efficiency deviation are satisfied at the same time is found, and the middle point of this region is selected as an optimal point for this optimization.

Regarding the design optimization results, the optimal camber angle of hub and tip is greater than the initial design by free vortex design concept, while the optimal camber angle in mid-span is lower than the initial design. The tip setting angle of the optimal model is slightly larger than the initial design by 2 deg (refer to Figs. 8 and 9).

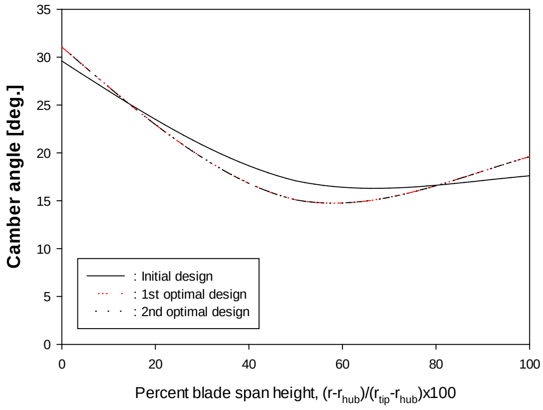

Fig. 8 Spanwise distributions of camber angle

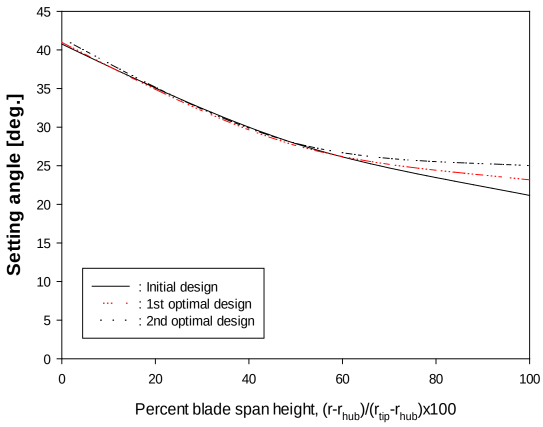

Fig. 9 Spanwise distributions of setting angle

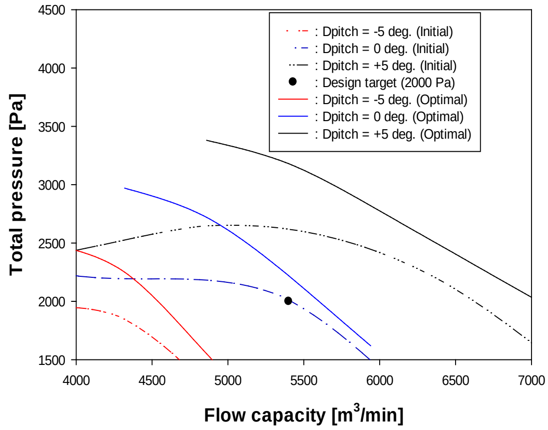

Fig. 10 Total pressure curves of the optimal and the initial fan models

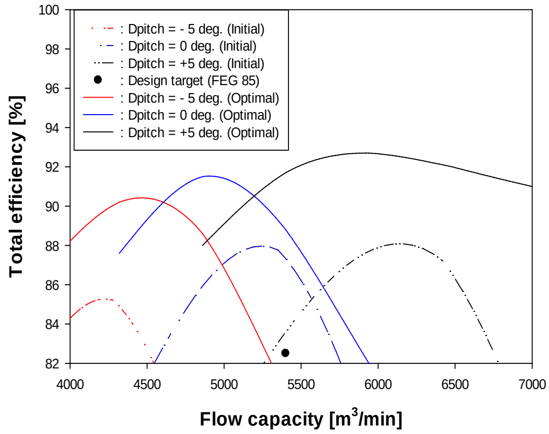

Fig. 11 Efficiency curves of the optimal and the initial fan models

Total pressure curves of the optimal and the initial fan models are predicted by CFD simulations at different variable-pitch conditions and compared in Fig. 10. As shown in Fig. 10, the total pressure curves of the optimal fan model show higher total pressure and more stable performance characteristics without surge up to the low flow rate range when compared with the initial design. . On the other hand, the initial design shows inferior performance characteristics in which the total pressure low compared to the optimal fan model and the pressure decreases rapidly under low flow conditions.

Fig. 11 compares the efficiency characteristics between the optimal design and the initial design. The design point efficiency of the optimal model is 91.5%, which improved by 3.7% compared to the initial design model, 87.8%, Through this design optimization, the deviation of the efficiency change due to variable-pitch operation is reduced from 1.10 % to 0.76%.

4. CONCLUSIONS

The present study proposes an optimization method for the multi-objective design optimization problem of variable-pitch axial flow fan. CFD modelling and simulation are used to construct a meta-model of axial flow fan design, and the meta-model is verified by comparing with precise CFD simulations. The meta-model is used as simulation engine of multi-objective optimization problem. Using the meta-model, a Pareto front is created to maximize design-point fan efficiency as well as to minimize fan efficiency deviation at variable-pitch operation conditions. Through the selection of an optimum design solution from the Pareto front, the optimal fan model shows the design-point efficiency improvement by 3.7% and reduces the efficiency deviation down to 0.76% when compared with the initial design.

ACKNOWLEDGEMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry & Energy(MOTIE), Republic of Korea. (No. 2021202080026B)

REFERENCES

[1] Wright, T., and Gerhart, P. M., 2009, *Fluid Machinery: Application, Selection and Design*, 2nd edition, CRC Press.

[2] Angelini, G., Bonanni, T., Corsini, A., Delibra, G., Tieghi, L. and Volponi, D., 2017, *Optimization of an axial fan for air cooled condensers*, Energy Procedia, Vol. 126, pp.754-761

[3] Edward, D.R., Fanny, B.C. and Jean, C.B., 2021. *Optimization of a high pressure industrial fan*, ASME Turbo Expo 2021 proceedings

[4] Kim, S.W., Choi, B.L., Choi, D.H., Lee, C. and Yang, S.H., 2022. *A study on a screening method for dimensionality reduction of large fluid machine optimization problems*, KSFM Journal of Fluid Machinery, Vol.25, pp.48-54

[5] KWT solution. 2023. *FANDAS code user manual*

[6] ANSYS Inc., 2023, *ANSYS CFX manual*, ANSYS

[7] PIDOTEC, 2022, *PIAnO manual*

[8] Lee, H.J., Choi, B.L., Choi, D.H., Lee, C. and Yang, S.H., 2025, *Design Optimization of Axial-flow Fan on Various Operation Conditions*, KSFM Journal of Fluid Machinery, Vol.28, pp.64-74

[9] Lee, C., Kim, S.W., Byun, H.T. and Yang, S.H., 2025, *High-efficiency Axial Flow Fan Design by Combining Through-flow Modeling, Optimization Algorithm and Computational Fluid Dynamics Simulation*, Journal of Applied Fluid mechanics, Vol.18, to be published