ADVANCED INTEGRATED DESIGN OPTIMIZATION SYSTEM USING 3D AERODYNAMIC AND AERO-ACOUTICS ANALYSES FOR DESIGN OF AN AXIAL FAN

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SUMMARY

In this work, an integrated fan design system, namely, Total FAN Plus-Axial®, was developed for non-specialists to carry out a series of design process, i.e., preliminary design, three-dimensional aerodynamic and aero-acoustic analyses, and design optimization for design of an axial fan. Flow analysis in the axial fan was conducted by solving three-dimensional Reynolds-averaged Navier-Stokes equations using the shear stress transport turbulence model. The noise analysis was implemented by solving the variational formulation of Lighthill's analogy. Finally, design optimization was performed using surrogate model to maximize the efficiency and to minimize the overall sound pressure level in the optimization part.

INTRODUCTION

High efficiency and low noise design is the most important goal for fan design. However, most small fan manufacturers have financial difficulties in technical development and performance tests. In designs of fans, a preliminary design is required on the basis of the approximate analysis method and empirical experimental model. And, in order to design high efficiency and low noise fans, three-dimensional computational fluid dynamics (CFD) and computational aero-acoustics (CAA) should be performed in order to understand the aerodynamic and aero-acoustic characteristics caused by the perturbation on the fan blade. To maximize the performance of the fans, multi-objective optimization technique based on CFD and CAA is the ideal approach. And, development of computer aided engineering (CAE) tool integrating these design processes would be very helpful for the designers who are not experts in CFD and design optimization.

Therefore, in this work, an integrated computational fan design system so called Total FAN Plus-Axial® has been developed to integrate a series of aerodynamic and aero-acoustic design processes; preliminary design, three-dimensional aerodynamic and aero-acoustic analyses, and multi-objective optimization, and applied to design of an axial fan. In this design, efficiency and overall sound pressure level (SPL) were simultaneously optimized in the design of the axial fan using three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations and surrogate modeling.

INTEGRATED FAN DESIGN SYSTEM

Total FAN Plus® software is an integrated fan design system which can carry out a series of design processes, i.e., preliminary design, three-dimensional aerodynamic and aero-acoustic analyses, and design optimization, for various types of fans. Total Fan Plus® system was developed to design four types of fans, i.e., axial, forward-curved and backward-curved blades centrifugal, and regenerate fans, by performing a series of design processes shown in Fig. 1. The design programs were named Total FAN Plus-Axial, -Sirocco, -Turbo, and –Regen® by Kim and Heo [1~4], for axial, forward- and backward-curved blades centrifugal, and regenerative fans, respectively.

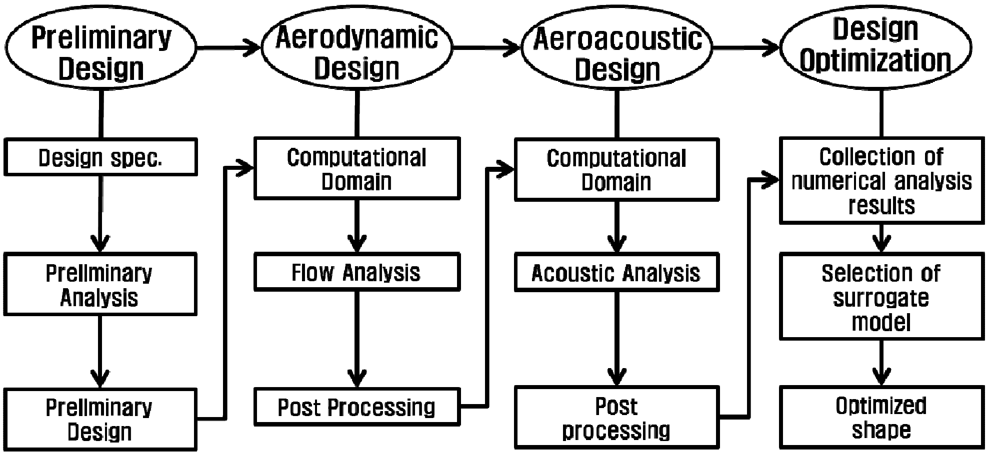


Figure 1: Flow chart of Total Fan Plus®

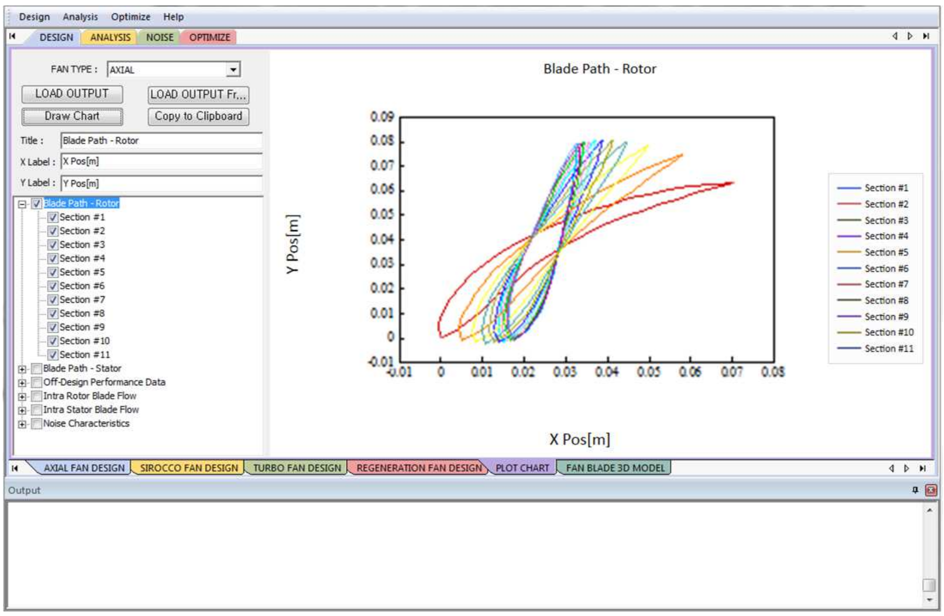


Figure 2: Graphic user interface (GUI) for preliminary design part of Total FAN Plus-Axial®

Table 1: Design specifications of the axial fan (Kim et al.[6])

Parameter	Value
Design volume flow rate, m3/min	60
Rotational speed, rpm	1170
Pressure rise, Pa	510
Tip diameter, mm	510
Tip clearance, mm	2
Number of blades	10

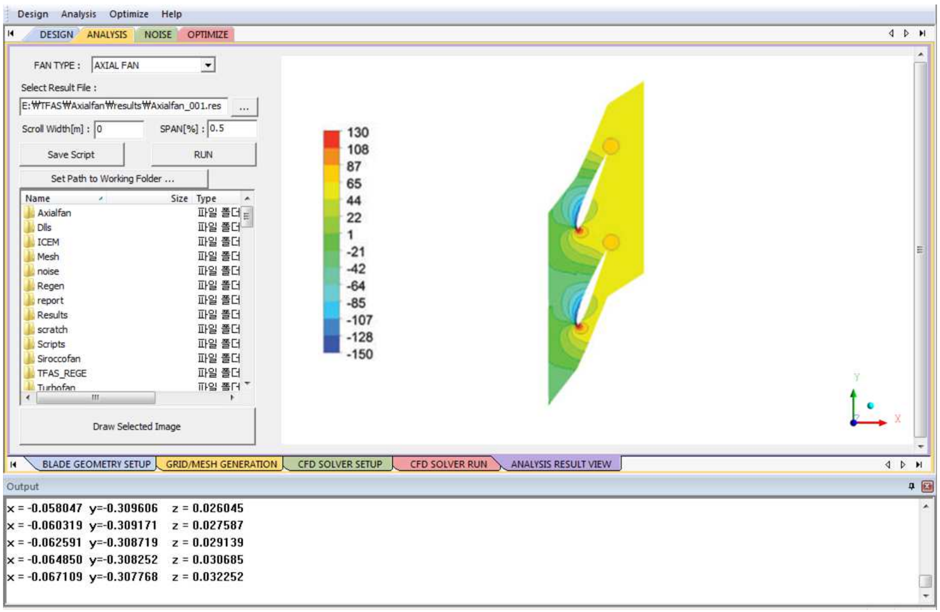


Figure 3: GUI of Total FAN Plus-Axial® for post-process of aerodynamic analysis

PRELIMINARY DESIGN

In preliminary design part, a computerized preliminary design system [5] was used for constructing geometry and predicting aerodynamic performance of an axial fan based on simple analytical methods as shown in Fig. 2. The computerized preliminary design system also predicts both the aerodynamic and aero-acoustic performances of the axial fan on the basis of simple analytical methods. The computerized preliminary design system predicts factors of the aerodynamic performance of fans (such as efficiency, pressure, and power) using simple analytical methods based on a mean-line approach coupled with empirical flow blockage, flow slip, and pressure loss models for required specifications. Based on the predicted mean-line flow and the performance prediction results, noise prediction is achieved using analysis models for discrete frequency and broadband noise models. Performance data of the axial fan, such as efficiency, pressure, power, and SPL and so on, are calculated on the basis of required specifications. In this study, the specifications used for the preliminary design of the axial fan are represented in Table 1. The axial fan considered in the preceding research by Kim et al. [6] was considered as a reference fan in this work. The required total pressure rise coefficient is 0.011 at the design flow coefficient of 0.041 and the number of blades is 10.

FLOW ANALYSIS

In the flow analysis part, three-dimensional computational domain is automatically generated on the basis of data obtained from the computerized preliminary design and configured to a various grid types, i.e., coarse, standard or fine grids. In this work, a hexahedra grid system was employed to generate the mesh in the computational domain, and grid dependency test was performed in a range of 100,000-430,000 nodes. Through the test results, 220,000 were determined as optimal number of grids. In the present simulation, by adjusting y+ less than 2, the low-Re version of the SST model has been employed. The commercial flow analysis code ANSYS CFX 15.0 [7] is used in this process. Namely, the blade profile creation and mesh generation for blade domain are performed through Blade-Gen and Turbo-Grid, respectively. The solutions are obtained by solving the incompressible RANS equations using finite volume method to discretize the governing different equations. The shear stress transport (SST) turbulence model was used as a turbulence closure. Air at 25 °C was used as working fluid. The commercial codes, i.e., Blade-Gen, Turbo-Grid, and CFX, are needed as external components of the Total FAN Plus® design system. The results of flow analysis for the axial fan were analyzed through Total FAN Plus-Axial® as shown in Fig. 3.

AERO-ACOUSTIC ANALYSIS

In the noise part, aero-acoustic analysis is carried out on the basis of the aerodynamic sources extracted from the results of unsteady flow analysis. The analysis is implemented in a finite/infinite element framework by solving the variational formulation of Lighthill's analogy, using the commercial CAA code, ACTRAN 13.0 [8]. The entire acoustic domain for the aero-acoustic analysis consists of axial blade passage domain and hemisphere domains for inlet and outlet parts as shown in Fig. 4. The grid system with minimum number of grids satisfied with the target element length ($L=c/6f$, where, c and f are speed of sound and maximum frequency value, respectively.) was constructed in the acoustic domain as recommended in the ACTRAN User's Guide [8]. The SPL values at virtual field points located on all azimuthal direction were calculated in each frequency domain through a direct frequency analysis on the basis of the aerodynamic sources predicted by unsteady RANS analyses, and the sound pressure contour in the computation domain was calculated at the each blade passing frequency (BPF) as shown in Fig. 5.

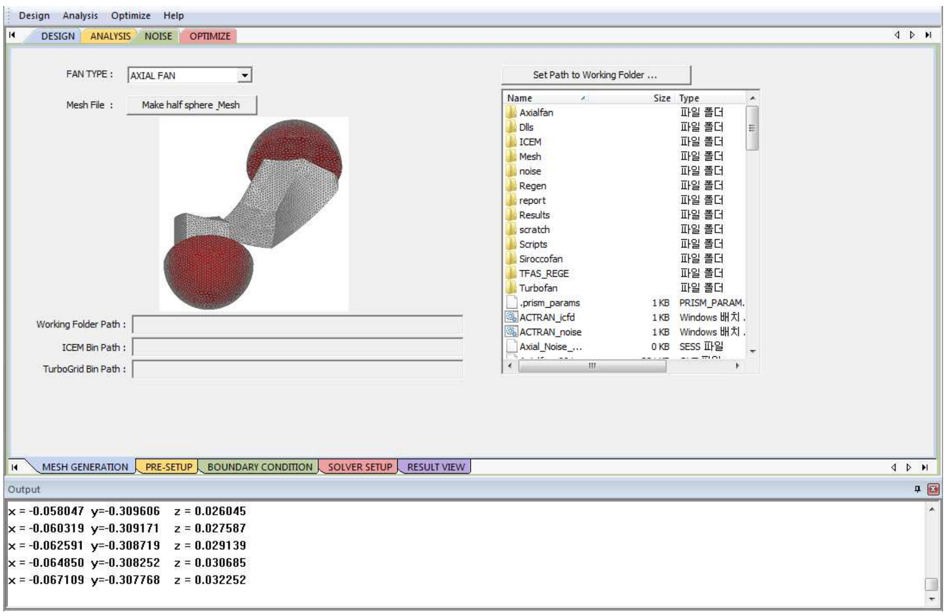
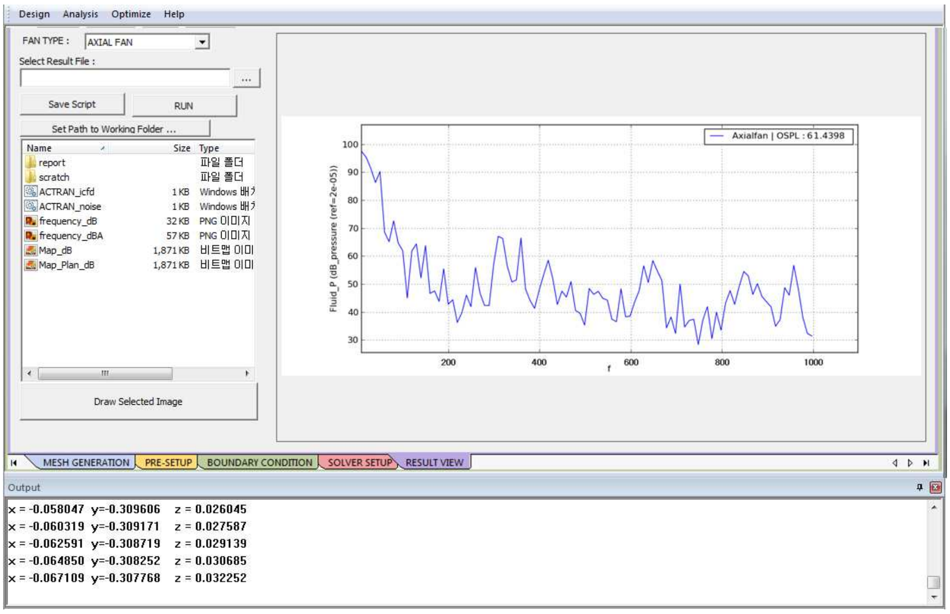
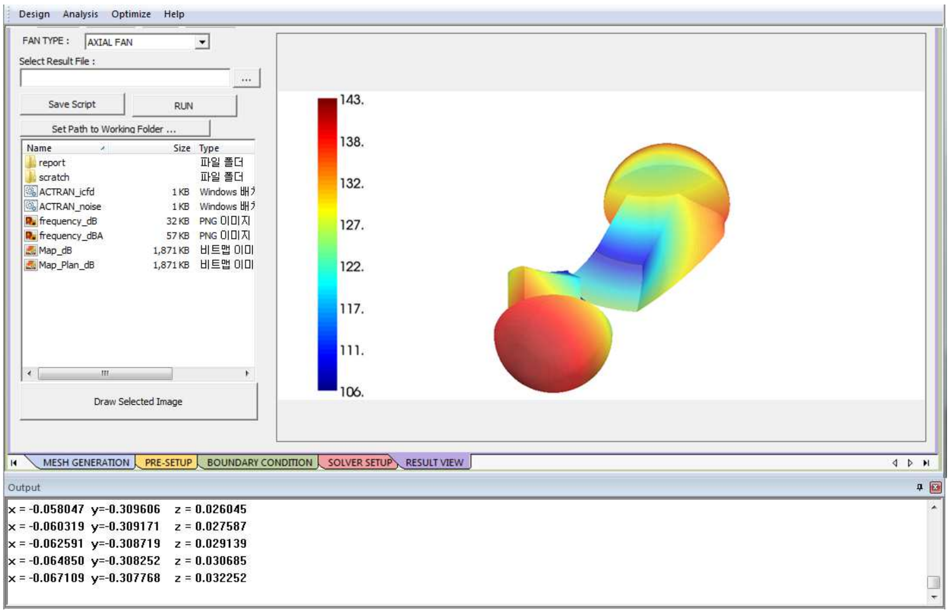


Figure 4: GUI of Total FAN Plus-Axial® for design process of aero-acoustic analysis



(a) Spectra



(b) Sound pressure contour

Figure 5: GUI of Total FAN Plus-Axial® for post process of aero-acoustic analysis

DESIGN OPTIMIZATION

In the optimization part, the design optimization of the axial fan is performed on the basis of the results of aerodynamic and aero-acoustic analysis. The surrogate models, i.e., Kriging (KRG), response surface approximation (RSA), radial basis neural network (RBNN), and predicted error sum of squares (PRESS)-based averaging (PBA) models, are used for optimization, and the sensitivity analysis of the design variables on each objective function is also performed.

In the present work, the RSA model was chosen as the surrogate model, and sweep and lean angles at the blade tip were used as the design variables for the optimization to simultaneously enhance the

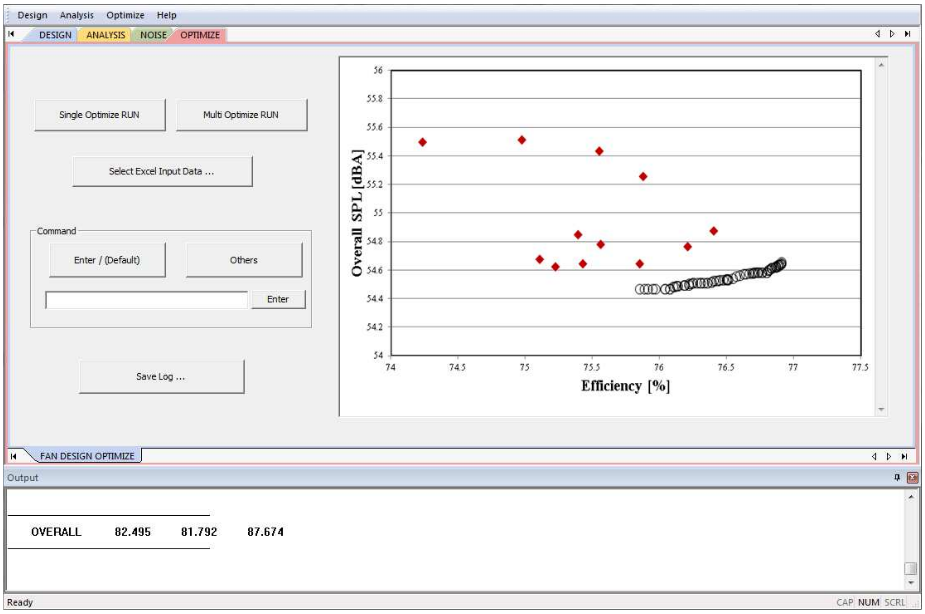


Figure 6: GUI of Total FAN Plus-Axial® for optimization design

Table 2: Results of multi-objective optimization (Kim et al. [6])

Design	Design variables		Efficiency		Overall SPL	
	Sweep angle	Lean angle	RSA	CFD	RSA	CAA
Reference	0	0	-	76.11	-	55.65
Optimum	4.68	-4	76.79	76.41	54.62	54.74

efficiency and overall SPL which are objective functions representing aerodynamic and aero-acoustic performances of the axial fan, respectively. Twelve design points are generated through a design-of-experiment technique, and base on the objective function values calculated on these design variables, the global Pareto optimal solutions (POSs) for two objective functions were obtained by hybrid multi-objective genetic algorithm (hybrid MOGA) using optimization part of Total FAN Plus-Axial® as shown in Fig. 6. Practical design of the axial fan can be selected among these POSs. In this study, a noise-oriented design was selected as the optimum design as shown in Table 2. The optimal design obtained using Total FAN-Axial® shows an increase in the efficiency and decrease in overall SPL as much as 0.4% and 1.6%, respectively, in comparison with the reference shape.

CONCLUSION

In this work, an integrated computational fan design system so called Total FAN Plus® has been developed to integrate a series of design processes to simultaneously optimize aerodynamic and aero-acoustic performances for four different types of fans; axial, forward-curved and backward-curved blades centrifugal, and regenerate fans. This system helps the designers to easily design the high efficiency and low noise fans. To validate the performance of this design system, multi-objective optimization of an axial fan has been performed using Total FAN Plus-Axial®, which is an integrated fan design system developed for design of axial fans. The preliminary design, three-dimensional CFD and CAA analyses, and multi-objective optimization were performed to simultaneously enhance the aerodynamic and aero-acoustic performance of the axial fan. The optimal shape of the axial fan showed the efficiency increased by 0.4% and the overall SPL decreased by 1.6%.

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