Springer

Journal of Mechanical Science and Technology 22 (2008) 1883~1888

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0727-8

Design of axial fan using inverse design method †

Kyoung-Yong Lee, Young-Seok Choi*, Young-Lyul Kim and Jae-Ho Yun

Thermal and Fluid System Team, Korea Institute of Industrial Technology, 35-3 Hongcheon-ri, Ipjang-myeon, Cheonan-si, Korea

(Manuscript Received April 16, 2008; Revised June 25, 2008; Accepted July 23, 2008)

Abstract

The axial fans for cooling condensers were designed by inverse design code TURBOdesign-1. The parameters of the inverse design were set by DOE (design of experiments). By changing the design parameters, such as the distribution of the blade loading, spanwise circulation distribution and stacking, 32 different fan designs were created for the screening of parameters. The overall performance and the local flow field of these fans were computed using a commercial CFD code. The results of the CFD computations were analyzed by DOE. The pressure rise and efficiency were selected as the main responses, and the main effects of the design parameters on the responses were discussed. The main design parameters for the optimum design of the fan were decided from the results of the screening procedure. We designed the optimum axial fan by RSM (response surface method). The design center fan was made by RP (rapid prototype) and the performance was tested using a fan tester based on AMCA standards. These procedures ensured proper screening of parameters and optimum design of the axial fan.

Keywords: Axial fan; Inverse design; Design of experiments (DOE); Optimum design

---

1. Introduction

Axial fans are widely used in the formation of air transport systems because of its simple structure. Its applicable areas include HVAC, vehicles, home appliances, computers and electronic appliance coolers, and it is usually used in ventilation and air cooling systems. As axial fans are widely used in home appliances and computers, functional improvement and noise reduction have become a critical issue in small axial fan designs. Traditional designing methods require much trial and error along with a designer's experience for the good design of the blade [1, 2]. The design controls the shape of the blades so there needs to be a precise appreciation of the decisive factors of the shape. Inverse design method, contrary to traditional designing methods, repeatedly designs a shape that meets the operational conditions and required functions and returns the designing result of the blade shape information [3-5]. In the inverse design method, blade loading is directly controlled to select the shape; therefore it is possible to reduce the time used for design modifications. Typical applications of inverse design method are pump design and shape modification [6]. In that research, the pump performance was improved by using the inverse design method in modifying an uneven flow field, which has been pointed out as a problem in past analyses on the shape. In axial fans, there exists a case where the inverse design method was used to change the blade loading distribution in designing a shape that successfully reduces noise [7].

In this study, an axial fan was designed by the inverse design method. The designed blade shape was put to CFD (computational fluid dynamics) for per-

† This paper was presented at the 9th Asian International Conference on Fluid Machinery (AICFM9), Jeju, Korea, October 16-19, 2007.

*Corresponding author. Tel.: +82 41 589 8337, Fax.: +82 41 589 8330
E-mail address: yschoi@kitech.re.kr

© KSME & Springer 2008

formance prediction. The DOE (design of experiments) method was used to analyze the effects of the designing parameters on the functionality of the fan. A RP (rapid prototype) was created on the design center shape to analyze the difference between numerical analysis and actual operating conditions, and the performance was measured with fan testers. The optimum design of the blade shape was obtained with parameters screened with the DOE method.

2. Design process

The designing procedures are as shown in Fig. 1. When the design specifications are decided, the validity is examined through theoretical analysis. The parameters for the inverse design program are decided for parameter screening, and the testing set is designed by DOE. The testing set is applied to the inverse design program to decide the shape, and CFD is used to predict the performance. The predicted results from CFD are analyzed by DOE to be applied in parameter screening for optimum design. The results are put through RSM (response surface method) for optimum designing, and the final shape is selected to satisfy the designing objectives. TURBOdesign-1, a commercial program for inverse designing, was used along with ANSYS CFX-11 for CFD and MINITAB R14 for DOE.

3. Design specification

In a fan-applicable system, whether the fan meets the functional requirements is the reference for overall performance and safety level of the system. Therefore a theoretical reasoning process on the functional requirements of the fan must be carried out first. The subject is a cooling fan for the condenser of vapor compression cooling system; 120 (W)×120 (L) mm in size, 57% hub-tip ratio, 4 m^3/min (CMM) of design volume flow rate, 100 Pa pressure. The basic shapes of conventional turbomachinery are decided by the size and its functional requirements, and the subject is a conventional propeller type [8]. Research on commercial fans which meet the design requirements showed that compared to conventional fans of the same size, they are of higher pressure per flow rate, with 6000 RPM and 65 dBA noise level. Considering the fact that the subject fan is used for a computer cooling system, the noise becomes a problem. Therefore the designing object was set to design a highly functional and efficient fan at the same RPM rate of commercial fans, and to reduce the number of revolutions to meet the functional requirements.

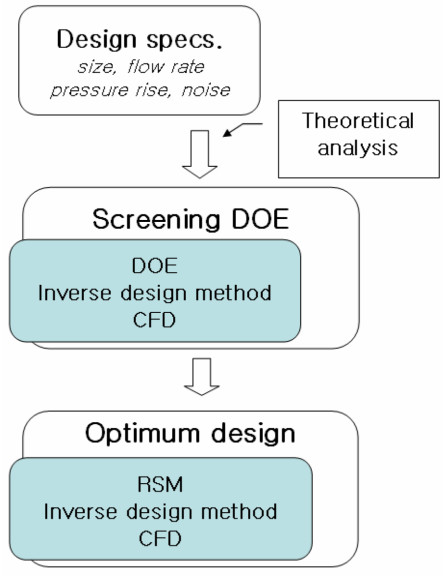

Fig. 1. Design procedure.

4. Inverse design parameters

In the inverse design method, loading distribution on the blades is modified to meet the required performance rate in deciding the fan shape [9]. However, this method is not merely about inputting desired designing conditions perfectly to get a desired optimum design. It controls the overall designing direction in loading on the blades, therefore making it easier to predict or control the outcome compared to traditional designing methods. Therefore the quality and efficiency of the design is improved by influence analysis on the parameters that could have influence on shaping the fan.

The designing parameters and variable range shown in Table 1 are largely divided into meridional shapes and blade loading distributions. In meridional shapes, the position of axial directions of hub and shroud are changed in the leading edge (LE) and trailing edge (TE). The blade loading distribution is divided into spanwise and streamwise distribution. In the case of spanwise distribution, it was expressed by the blade loading slopes of hub and shroud at TE (rVt_slope). Fig. 2 displays midspan and shroud, the starting and ending points of the straight part (NC and

Table 1. List of design parameters and range of variation.

Design parameter	Variable range	Base value
Meridional parameter		
LE_hub	0-2.5	0
LE_shr	0-2.5	0
TE_hub	22.5-25	25
TE_shr	22.5-25	25
Blade loading parameter		
rVt_slope	±20%	0
hub_slope	±20%	-0.87
hub_LE_load	±20%	0.32
mid_slope	±20%	-0.9
mid_LE_load	±20%	0.28
shr_slope	±20%	-1
shr_LE_load	±20%	0.22
stacking	±20%	25

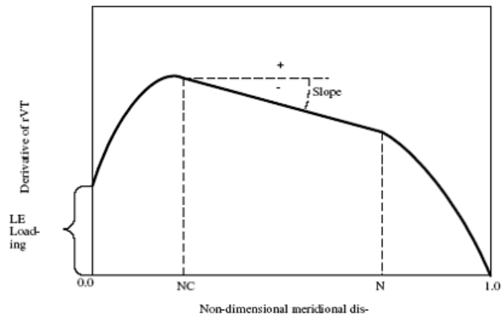

Fig. 2. Blade loading distribution in streamwise distribution [9].

ND), and the slope of the straight part. The research results on inverse design of box fans which are of a similar specific speed range, were used for distributional reference of blade loading in a streamwise direction [7]. NC and ND are fixed in the distribution, and the loads on LE of hub, midspan and shroud were selected as parameters, along with the slope of the straight part. Stacking, which is an important parameter in traditional axial fan design, was also included as a parameter.

5. Screening DOE

Parameter screening is an important step in judging the influence level of parameters at an early stage of design. To analyze the influence of the 12 design parameters shown in Table 1 on overall performance, the parameter range was changed to 2k level; in this case, 4096 probability cases exist. However, DOE can notably decrease the number with a bit of assumption. This study applied 2k fractional factorial design, with 32 design sets of resolution level 4 [10]. The Y-value is the reference for analyzing the results in examining the influence of parameters. Standard values in fan functionality include static pressure rise and efficiency at the design flow rate.

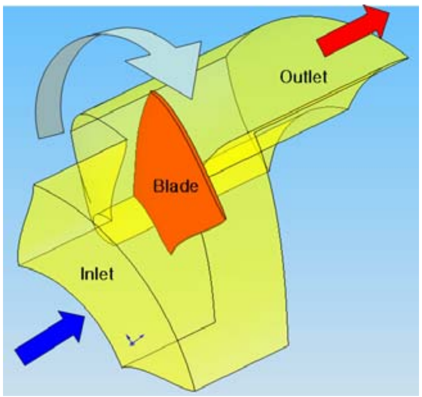

Fig. 3. Numerical anlysis domain.

6. Inverse design and CFD

The design parameter set decided by DOE were inserted into the inverse design program to get a converged shape. The designed shape is transformed into the input value for turbomachinery specific grid generator (ANSYS CFX-TurboGrid v11); 80,000 structured grids were created for analysis.

Numerical analysis was carried out by ANSYS CFX-11, a commercial CFD code. The numerical domain included only the fluid flow regimes with one blade while taking periodic condition into consideration, as shown in Fig. 3. In the entrance and the exit, the meridional planes are extended in the axial direction. Atmospheric pressure conditions were applied to the entrance, and mass flow conditions to the exit. The blade and hub are set to rotating wall condition, and the stationary shroud to non-rotating wall condition. The tip clearance between the rotating blade and case was not taken into consideration. Rises in static pressure and static efficiency at the flow rate of design conditions were calculated from the numerical analysis results, and were used as the Y-value of DOE.

7. Results of screening DOE

The main effect plotting for rises in static pressure and static efficiency due to parameter changes is shown in Figs. 4 and 5. Except for the parameter related to the position of the shroud in the meridional side of the TE (TE_shr), the effect of changes in parameter on the Y-value is generally similar. In the screening stage, verification of the parameter selection and range through the initial analysis results is necessary. Since there exists a parameter which has a large effect on the performance and it has an increasing or decreasing tendency in the range, the parameter selection and range are deemed appropriate.

Analyzing the results shows that the effect of the rVt_slope was comparatively the largest for rise in static pressure, followed by mid_slope and shr_slope. In the case of static efficiency, mid_slope, shr_slope and LE_shr are large influences. Meridional shape-related LE_hub, LE_shr, TE_hub and TE_shr are more influential to the rise in static efficiency than static pressure. In the meridional shape, a smaller-size, high-efficiency-oriented approach can be used. In blade loading distribution analysis, rVt_slope at TE displayed a large influence, and the hub side blade loading is better than shroud side blade loading in static pressure rise and static efficiency. At 57% hub-tip ratio, the blade loading distribution of the midspan is relatively important; it is shown in the parameters related to the blade loading distribution in streamwise distribution. This contradicts designing results of the traditional method where the blade shape distribution of hub and shroud are smoothly connected, and it has been introduced in pump designs. The influence of the parameter was decided by result analysis, and from that the parameters for optimum design were selected. rVt_slope, mid_slope and shr_slope are selected as the optimum design parameters, and other parameters were fixed in consideration of pressure increase and efficiency.

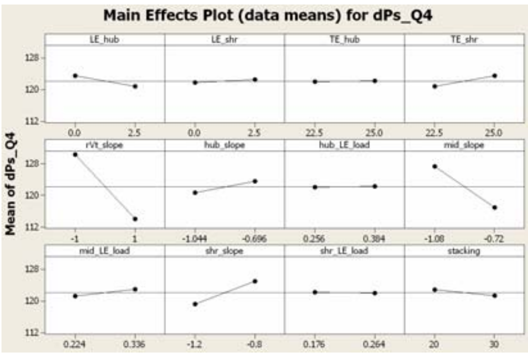

Fig. 4. Main effects plot for static pressure rise.

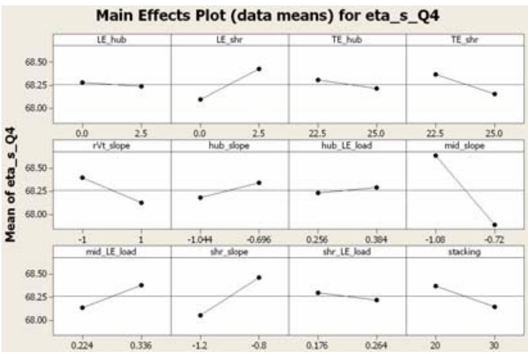

Fig. 5. Main effects plot for static efficiency.

8. Optimization

Optimum design parameters were selected through parameter screening, and design set was chosen through RSM. A 3-parameter central composite method from response surface method was used and the cube model (CCC, central composite circumscribed) was applied [11]. The cube model, in the case of the 3-parameter method, is where the parameter ranges are the vertexes of a hexahedron, and the range is increased until the circumscribed sphere meets the axis. The overall design set consists of 20, including 5 sets of repeated central values. The set inserts the parameter values into the inverse design program in the same manner of screening DOE, then calculates the Y-value through CFD. The BEP (best efficiency point) flow rate was added to the Y-value to design the highest efficiency at design condition, along with rises in static pressure and static effi-

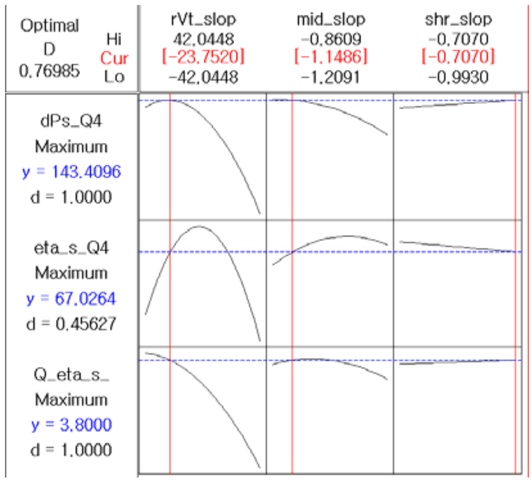

Fig. 6. Result of optimum design.

ciency; the result is shown in Fig. 6.

When multiple Y-values exist, it is difficult to carry out optimum design which meets the requirements of all values. If this is the case, weighted value is added to the Y-value. In this study, not only functionality but also noise is an important issue, so the number of revolutions was decreased to aim for noise reduction. For the final Y-value, the rise in static pressure and the flow rate of BEP was set to the maximum for RSM design set, and a midpoint value for static efficiency. The weighted values for the Y-value were applied in the order of: rise of static pressure, efficiency maintenance, and flow rate at BEP. In the optimum design results of Fig. 6, the two parameters excluding shr_slope show a curve effect. This can be interpreted as having an optimum value. The overall desirability level at optimum design results is 0.76985 and the static pressure rise and BEP flow rate are both satisfactory, with the exception of efficiency. However in the case of desirability, although it is a reference for the satisfactory level of design requirements, a subjective opinion of the designer can be included depending upon the characteristic of the Y-value. Therefore it is important to decide whether the designing requirements have met an appropriate level compared to the standardized value.

The design optimization result was compared with initial reference value (screening DOE) and the result from RSM reference value, and is shown in Table 2. The relative comparison of the midpoint value result of screening DOE was added to the result of RSM_optimum. The optimum design result slightly decreases in efficiency, but raises the static pressure by 28.2%. Considering that the fan outside diameter, hub-tip ratio, axial direction length and number of revolutions are all the same, it is considered that an optimum blade that meets the design requirements was designed in this study.

9. Fan test and loss analysis

The loss of axial fans differs according to the flowing pattern of the applied system. The functionality and sound level change is dependant on whether the entrance and exit of axial fan is open, the flowing Fan test and loss analysis pattern of the entrance, and the position of motor support [12, 13]. In this study, the influences of entrance and exit, flow pattern of the entrance, and the tip clearance between the blade and case was not taken into consideration in the optimization process. Therefore it is necessary to analyze the level of functional decrease to reflect on the design modification. Conventional fan motors which displayed a similar level of performance were used.

Midpoint value of RSM was used to build an axial fan, and its performance was measured. (Fig. 7) 3-dimensional modeling information provided by the inverse design program was used in forming the shapes of the blades, and the case was built in a cylindrical shape with 1 mm of gap between the blade tip and case in the radial direction.

The fan testing results are compared with results from the CFD in Fig. 8. The original results of fan test showed a change in the rotating speed of the fan due

Table 2. Comparison of overall performance in the case of DOE center, RSM center and optimum design.

Case	dPs_Q4 (Pa)	eta_s_Q4 (%)	Q_eta_s_max (CMM)
Screening DOE center	111.879	67.94	3.65
RSM center	136.594	68.06	3.73
RSM optimum.	143.409 (+28.2%)	67.03 (-1.3%)	3.8 (+4.1%)

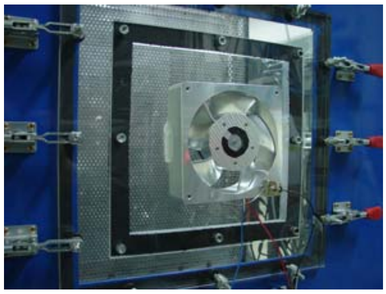

Fig. 7. Photograph of fan test.

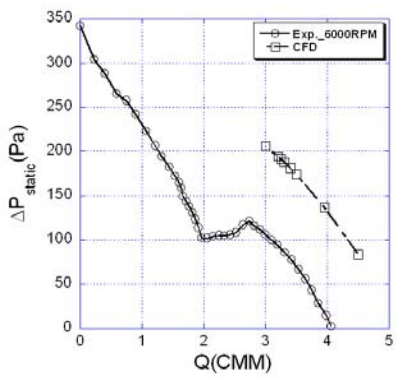

Fig. 8. Comparison of performance curve with results of Exp. and CFD.

to the motor characteristics, so it was normalized to match the rotating speed in the CFD as 6000 RPM. The overall performance curve shows similar patterns in slope, but a large difference exists in the flow rate at design conditions. The difference between the test and CFD results can be explained by the loss occurred. The flow field of CFD is a duct type where entrance and exit parts are extended, and it was assumed that the inflow in was uniform velocity.

However, in test case, the entrance is of sudden contraction type and the exit is of sudden expansion type, as shown in Fig. 7. In this case loss occurred at the entrance and exit areas, and theoretically a decrease in pressure of about 110 Pa can be expected [14]. For a precise analysis, the blades were removed, and then the fluid-induced pressure decreases in the hub and case were measured. Test results show that about 138 Pa of decrease in pressure occurred, and this exactly matches the gap between the testing and numerical analysis results from the flow rate at design conditions.

The directions for design modifications were confirmed through the fan test on RSM design model and loss analysis. Examination of design requirements with regards to flow loss at the initial design stage must be preceded for a precise design. There also needs to be a case design to minimize flow loss.

10. Conclusion

This study introduced an inverse design method to design an axial fan. In order to analyze the influence of the shaping parameters on the overall performance, the design set was decided with DOE, and the performances of each designed shape were assessed by CFD. The influence level of parameters was analyzed to select parameters for optimum design, and the optimization was carried out through RSM. As a result, the static pressure was raised by 28.2% and the efficiency decreased by 1.3%, compared to the reference value at the initial parameter-screening stage. The flow loss in the entrance and exit areas should be taken into consideration in designing fans through a fan test on RSM design-based model and loss analysis, and the design optimization of a case that minimizes the flow loss is required as well.

Acknowledgments

This research is implemented as a part of the project "Technology Development of Advanced Cooling System" managed by Korea Research Council for Industrial Science & Technology. The authors gratefully appreciate the support.

References

[1] Eck, B., Fans Design and Operation of Centrifugal, Axial-Flow, and Cross-Flow Fans, Oxford Pergamon Press, New York, USA, (1973).

[2] R. A. Wallis, Axial Flow Fans and Ducts, A Wiley-Interscience Publication, USA, (1983).

[3] M. Zangeneh,, Inviscid-viscous interaction method for 3d inverse design of centrifugal impellers, *ASME Journal of Turbomachinery,* 116 (1994) 280-290.

[4] A. Demeulenaere and R. Van den Braembussche, Three-dimensional inverse method for turbomachinery blading design, *ASME Journal of Turbomachinery,* 120 (1998) 247-255.

[5] J. S. Kim and W. G. Park, Optimized inverse design method for pump impeller, *Mechanics Research Communications,* 27 (4) (2000) 465-473.

[6] M. Zangeneh, A. Goto and H. Harada, On the design criteria for suppression of secondary flows in centrifugal and mixed flow impellers, *ASME Journal of Turbomachinery,* 120 (1998) 723-735.

[7] H. Okamoto, M. Zangeneh, H. Watanabe and A. Goto, Design of a box fan rotor using 3-D inverse design method, *IMechE Engineering Publications,* 4 (2004) 129-140.

[8] T. Wright, Fluid Machinery: Performance, Analysis and Design, CRC Press, New York, USA, (1999).

[9] TURBOdesign^{-1} version 2.3.0b6, Documentation, Advanced Design Technology Ltd (www.adtechnology.co.uk), London, (2006).

[10] C. R. Hicks and K. V. Turner, Fundamental Concepts in the Design of Experiments, 5th ed., Oxford University Press, New York, USA, (1999).

[11] R. H. Myers and D. C. Montgomery, Response Surface Methodology: Process and Product Optimization Using Designed Experiments, 2nd ed., A Wiley-Interscience Publication, USA, (2002).

[12] V. B. Tupov, The influence of several design features of the inlet and outlet of an axial fan on its characteristics, *Thermal Engineering,* 44 (11) (1997) 950-955.

[13] F. P. Bleier, Fan Handbook, 2nd ed, Application and Design, McGraw-Hill, New York, USA, (1997).

[14] Idelchik, I. E., Handbook of Hydraulic Resistance, 3rd ed., begell house, USA, (1996).