SCIENCE CHINA
Technological Sciences

January 2010 Vol. 53 No.1: 75–79
doi: 10.1007/s11431-009-0415-7

Design of low noise airfoil with high aerodynamic performance for use on small wind turbines

Taehyung KIM, Seungmin LEE, Hogeon KIM & Soogab LEE*

Department of Mechanical and Aerospace Engineering, Seoul National University, 599 Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea

Received September 29, 2009; accepted October 15, 2009

Wind power is one of the most reliable renewable energy sources and internationally installed capacity is increasing radically every year. Although wind power has been favored by the public in general, the problem with the impact of wind turbine noise on people living in the vicinity of the turbines has been increased. Low noise wind turbine design is becoming more and more important as noise is spreading more adverse effect of wind turbine to public. This paper demonstrates the design of 10 kW class wind turbines, each of three blades, a rotor diameter 6.4 m, a rated rotating speed 200 r/min and a rated wind speed 10 m/s. The optimized airfoil is dedicated for the 75% spanwise position because the dominant source of a wind turbine blade is trailing edge noise from the outer 25% of the blade. Numerical computations are performed for incompressible flow and for Mach number at 0.145 and for Reynolds numbers at 1.02×10^6 with a lift performance, which is resistant to surface contamination and turbulence intensity. The objectives in the design process are to reduce noise emission, while sustaining high aerodynamic efficiency. Dominant broadband noise sources are predicted by semi-empirical formulas composed of the groundwork by Brooks et al. and Lowson associated with typical wind turbine operation conditions. During the airfoil redesign process, the aerodynamic performance is analyzed to reduce the wind turbine power loss. The results obtained from the design process show that the design method is capable of designing airfoils with reduced noise using a commercial 10 kW class wind turbine blade airfoil as a basis. Therefore, the new optimized airfoil showing 2.9 dB reductions of total sound pressure level (SPL) and higher aerodynamic performance are achieved.

wind turbine, aerodynamic noise, airfoil self noise, low noise airfoil design

Citation: Kim T, Lee S, Kim H, et al. Design of low noise airfoil with high aerodynamic performance for use on small wind turbines. Sci China Tech Sci, 2010, 53: 75–79, doi: 10.1007/s11431-009-0415-7

Nomenclature

A, B: empirical spectral shape based on the Strouhal number
C_d: drag coefficient
C_l: lift coefficient
D_h: directivity function
f: frequency
G_i: empirical function
h: trailing edge thickness
K_i: empirical relation ($K_i(Re_c)$)
ΔK_i: empirical relation ($\Delta K_i(\alpha, Re_{\delta^*})$)
L: span of the airfoil section
M: local blade inflow Mach number
r_e: effective observer distance
Re: Reynolds number
Re_c: Reynolds number based on chord
SPL: sound pressure level
St: Strouhal number ($f\delta^*/U$)
St'': Strouhal number based on h
St''_{peak}: peak Strouhal number ($St''_{peak}(h/\delta^*_{avg})$)
U: local mean velocity
α: angle of attack
δ^*: boundary layer displacement thickness
δ^*_{avg}: average displacement thickness for both sides of

*Corresponding author (email: solee@snu.ac.kr)

the airfoil

Ψ: solid angle between both airfoil surfaces just upstream of the trailing edge

1 Introduction

Wind power has come into footlights as alternative energy sources to substitute for the fossil fuels. The installed capacity is increasing radically every year. However, wind turbine noise is one of the major hindrances for the widespread use of wind power. The noise source mechanisms must be investigated in order to reduce wind turbine noise. Therefore, comprehensive research efforts have been performed to improve the understanding of wind turbine aeroacoustics and develop the low noise blades in the Europe JOULE-III project and U.S. NREL [1, 2]. For those researches, aerodynamic noise from the blades is generally considered to be the dominant noise source, provided that mechanical noise is adequately reduced [3]. The aerodynamic noise sources can be divided into low-frequency noise, inflow turbulence noise, and airfoil self-noise. Low-frequency noise is generated when the rotating blade encounters localized flow deficiencies due to the flow around a tower, inflow gradients, or wakes shed from the other blades, and is considered to be of little importance if the rotor is placed upwind the tower [3]. Inflow turbulence noise is caused by the interaction of upstream atmospheric turbulence with the leading edge of the blade, depends on the atmospheric conditions, and causes a broadband radiation [3]. Airfoil self-noise is mainly associated with the laminar or turbulent boundary layer on the blade surfaces. This type of noise can have tonal or broadband characteristics, and is considered to be caused by several mechanics, such as trailing edge noise, laminar boundary layer vortex shedding noise, tip noise, separated or stalled flow noise, and blunt-trailing-edge noise [3].

The work presented herein focuses on the numerical aerodynamic and aeroacoustic analysis of low noise airfoils that are candidates for use on small wind turbines having rated power of 10 kW. However, without knowledge of both the aerodynamic and aeroacoustic performance of airfoils, it is frustrating in making decisions on new blade designs. This is particularly true for small wind turbines, which operate at low Reynolds number of about 1 million, at which airfoil aerodynamic characteristics are both sensitive and difficult to predict. Thus, it is important to be conducted by the numerical methods which can predict the dominant components of noise sources reliably. This paper describes the design optimization procedure of a low noise airfoil. The numerical optimization works directly on the airfoil shape providing a direct and interactive design procedure, where multiple design objectives for aerodynamics and aeroacoustics may be treated simultaneously. Wind turbine noise sources are predicted by numerical methods and empirical formulas. After the optimization procedure is applied to this result, the new optimized airfoil is derived.

2 Method for airfoil design

The airfoil design of wind turbine blades consists of complex procedures generally. The work described herein focuses on the numerical optimization design of low noise airfoil for use on small wind turbines. Hence, the optimized airfoil geometry and extended blade were derived from design optimization procedures. The developed two-dimensional airfoil and three-dimensional blade were validated with flow analysis and noise analysis program which are developed through the previous works [4, 5].

The two-dimensional airfoil design tool consists of three phases: airfoil geometry generation, aerodynamic performance analysis, and noise analysis. It uses a direct method where numerical optimizations are coupled with the flow solver X-FOIL [4], which is a panel code with viscous interaction, and the noise solver NAFNOISE which is a semi-empirical code composed of Lowson's equation for turbulence inflow noise [6], and 2D empirical formulas of Brooks et al. for airfoil self noise [5].

2.1 Design strategy

For airfoil design stage, the design variables are the control points that describe the airfoil shape. In this case, there are 12 design variables which form the airfoil shapes, of which 6 are variables for a suction side, and the others for a pressure side. Based on this airfoil shape result, flow analysis was performed to provide C_l or C_d near the design angle of attack. In the noise analysis, turbulence inflow noise and laminar boundary layer vortex shedding noise were not considered. Because turbulence inflow noise (TIN) is caused by natural atmospheric turbulence, TIN intensity is mainly affected by the atmospheric turbulence and terrain roughness at which wind turbines are located. For laminar boundary layer vortex shedding noise, it is of minor importance due to surface contamination from bugs and dust in the real operation condition. Hence, the design variables for noise optimization are to reduce turbulent boundary layer trailing edge noise. A passive optimization method was used to avoid the large number of necessary flow and noise calculations for abnormal airfoil shapes, and to develop the low noise airfoil.

2.2 Flow analysis

Flow calculations during the optimization were conducted using X-FOIL. For a given *Re*, Mach number, and angle of attacks (AOAs), X-FOIL provides C_l and C_d. The baseline airfoil model is the blade section for use on commercial small wind turbines having rated power of 10 kW. The wind turbine model uses the same airfoil throughout the blades and its geometry factors and operation conditions are shown by Table 1.

The previous experimental results showed that the dominant source of a wind turbine blade is trailing edge noise from the outer 25% of the blade [7]. For wind turbine rotating blades, the airfoil which has 20% or more thickness is generally used for the root airfoil, and has low lift to drag ratio [8]. DU 91-W2-250 and DU 93-W-210 airfoils which are developed for wind turbine airfoils have good aerodynamic performance and their maximum lift to drag ratio values are 80 or more [9]. According to the results of paper survey, the baseline airfoil was selected to be located at 75% spanwise directional position. Consequently, the new optimized airfoil was managed to be 75% blade position from root to tip, and to have airfoil thickness 20% or less, and to have maximum lift to drag ratio 80 or more around the operation angle of attack.

2.3 Noise analysis

Early researchers, e.g. Brooks et al. [5] divided the noise emission from wind turbines into five different sources: (1) tip noise, (2) turbulent boundary layer trailing edge noise, (3) laminar boundary layer vortex shedding noise, (4) inflow turbulence noise, (5) blunt trailing edge noise. The intensity of turbulent boundary layer trailing edge noise is known to be directly proportional to the turbulent boundary layer thickness, δ^*, and the fifth power of the mean velocity or Mach number, M^5, and inversely proportional to the square of the distance between the observer and the airfoil trailing edge. Turbulent boundary layer noise can originate from both the suction and pressure sides of the airfoil. The total sound pressure level is given as follows [11]:

$$\mathrm{SPL}_{\mathrm{total}} = 10\log\left(10^{\mathrm{SPL}_p/10} + 10^{\mathrm{SPL}_s/10} + 10^{\mathrm{SPL}_\alpha/10}\right), \qquad (1)$$

$$\mathrm{SPL}_p = 10\log\left(\frac{\delta_p^* M^5 L\overline{D_\mathrm{h}}}{r_\mathrm{e}^2}\right) + A\left(\frac{St_p}{St_1}\right) + \left(K_1 - 3\right) + \Delta K_1, \quad (2)$$

$$\mathrm{SPL}_s = 10\log\left(\frac{\delta_s^* M^5 L\overline{D_\mathrm{h}}}{r_\mathrm{e}^2}\right) + A\left(\frac{St_s}{St_1}\right) + \left(K_1 - 3\right), \qquad (3)$$

$$\mathrm{SPL}_\alpha = 10\log\left(\frac{\delta_s^* M^5 L\overline{D_\mathrm{h}}}{r_\mathrm{e}^2}\right) + B\left(\frac{St_s}{St_2}\right) + K_2. \qquad (4)$$

Table 1 Turbine geometry factors and operation conditions

Blade diameter	6.4 m
Hub height	18.0 m
Rated wind speed	10 m/s
Number of blades	3
Rated RPM	200

Another source of airfoil self noise is vortex shedding from a blunt trailing edge. This noise source will dominate the totally radiated noise if the thickness of the trailing edge is significantly larger than the thickness of the boundary layer at the trailing edge. The sound pressure level is predicted by the empirical relation as follows [11]:

$$\mathrm{SPL}_{\text{TEB-VS}} = 10\log\left(\frac{\delta_p^* M^5 L\overline{D_\mathrm{h}}}{r_\mathrm{e}^2}\right) + G_4\left(\frac{h}{\delta_{\mathrm{avg}}^*}, \Psi\right) + G_5\left(\frac{h}{\delta_{\mathrm{avg}}^*}, \Psi, \frac{St''}{S''_{\mathrm{peak}}}\right). \qquad (5)$$

Turbulent boundary layer trailing edge noise is generally considered to be the most important source of airfoil self noise for modern wind turbine blades of high-frequency noise and is broadband [10]. This is the reason for focusing on this source. Using these results of noise analysis, the airfoil shape is redesigned through recursive procedures.

3 Results and discussion

Figure 1 illustrates the comparison of airfoil geometry between baseline and optimized airfoil. Though the optimized airfoil shape is not different from the baseline significantly, the thicknesses of the pressure side and suction side are reduced and the maximum thickness location is moved from x/c = 0.361 (baseline) to x/c = 0.372 (optimized airfoil). The maximum thickness of baseline and optimized airfoil is 0.211 and 0.173 in respect to the chord length, respectively. Figures 2 and 3 show the lift coefficients and lift to drag ratios of baseline and optimized airfoil, respectively. Figure 4 also shows that the C_l/C_d of the optimized airfoil is about 90 near the design angle of attack, 7°, and improved by 51% in comparison with that of baseline for $Re = 1.02\times10^6$. These results are satisfied with the desired aerodynamic performances.

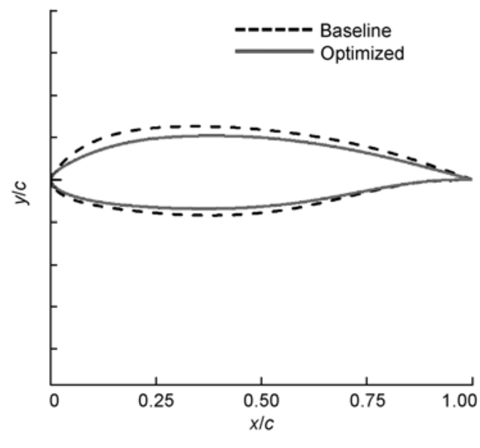

Figure 1 Airfoil geometry comparison (baseline and optimized airfoil).

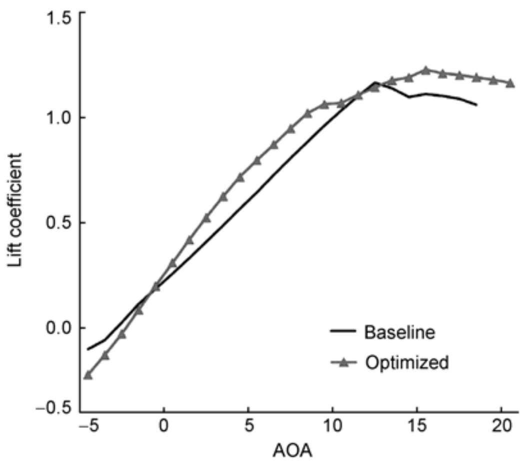

Figure 2 Lift coefficients for baseline and optimized airfoil.

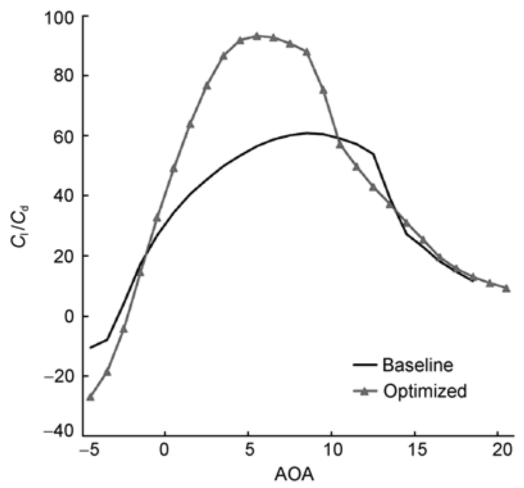

Figure 3 Lift to drag ratios for baseline and optimized airfoil.

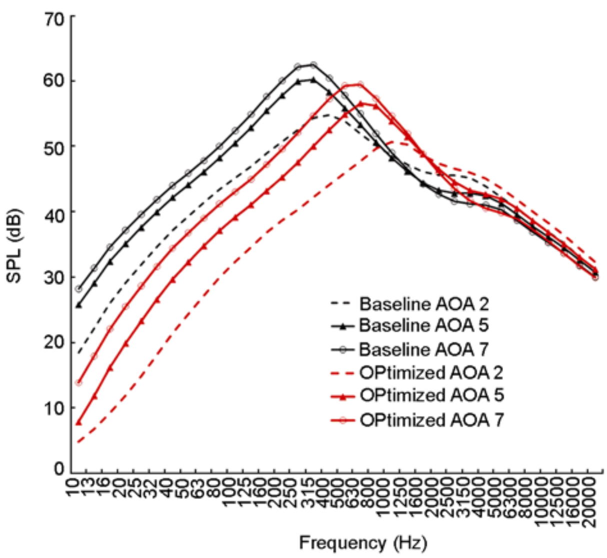

Figure 4 SPL spectra for baseline and optimized airfoil.

To measure noise levels, the A-weighted scale is widely used. Because noise is experienced at a wide range of frequencies and the human ear dampens low frequencies in these ranges. Here, sound pressure level (SPL) without A-weighted scale is used to investigate the noise reduction of the optimized airfoil and wind turbine blade. There are previous results that noise levels without A-weighted scale are more appropriate than noise levels with A-weighted scale because the detectable amount of noise reduction with A-weighting is very weak [11].

Figure 4 illustrates that the integrated spectrum for the optimized airfoil has similar shapes as the baseline spectrum, but seems to be shifted toward high frequencies below 2500 Hz ranges. The peak level is the summation of the two different components: suction side, and separated flow. Since the overall thickness is reduced in the optimized airfoil, the boundary layer thickness is also reduced and the turbulent eddies passing the trailing edge in the boundary layer have small scales. That is considered to be the reason why SPL shifted toward high frequencies ranges. It is known that the length-scale of the turbulent eddies is the important parameters describing the boundary-layer turbulence [3]. In the higher frequency range above 5000 Hz, the integrated spectrum for the optimized airfoil has the same shape as the baseline spectrum. The pressure side turbulent boundary layer trailing edge noise is dominant in these ranges. Howe [12] showed that the exactness of the trailing edge is of importance only for relatively high frequency and trailing-edge noise can also be reduced by giving the trailing edge a serrated shape. Hence, the design optimization including trailing edge modification should be investigated to reduce high frequency noise components for the future works. Figure 4 also shows that the overall SPL reduction of the optimized airfoil at an angle of attack 7° is 2.9 dB. Thus, the result when analyzing the SPL is that it is possible to reduce the noise emission compared to the baseline airfoil and the new optimized airfoil showed a higher aerodynamic performance.

4 Conclusions

Airfoil low noise design optimization was carried out on a 10 kW-class wind turbine with one baseline blade. The airfoil was developed considering low noise and high aerodynamic performance. For this purpose, the flow analysis tool, X-FOIL, and the noise analysis tool, WINFAS, were used. The new optimized airfoil was managed to be 75% blade position from root to tip and the C_l/C_d of the optimized airfoil was about 90 at the design angle of attack, 7°, and improved by 51% in comparison with that of baseline. SPL without A-weighted scale was used to investigate the noise reduction because the detectable amount of noise reduction with A-weighting is very weak. The integrated spectrum for the optimized airfoil has similar shapes as the baseline spectrum, but seems to be shifted toward high frequencies below 2500 Hz ranges and the overall SPL reduction of the optimized airfoil at the design angle of attack is 2.9 dB.

This work is the outcome of a Manpower Development Program for Energy & Resources supported by the Ministry of Knowledge and Economy (MKE). This work was supported by New and Renewable Energy R&D Program (Grant No. 2009T100100231) under Ministry of Knowledge and Economy, Republic of Korea.

1 Oerlemans S. Wind tunnel aeroacoustic tests of six airfoils for use on small wind turbines. NREL SR-500-35339, 2004
2 Guidati G, Bareiss R, Wagner S, et al. Development of design tools for reduced aerodynamic noise wind turbine. Proc. of the European Union Wind Energy Conference and Exhibition, Goteborg, 1996. 778–781
3 Wagner S, Bareiss R, Guidati G. Wind Turbine Noise. Berlin Heidelberg: Springer-Verlag, 1996
4 Drela M. An analysis and design system for low Reynolds Number airfoils. Conference on Low Reynolds Number Aerodynamics, University of Notre Dame, Indiana, USA, 1989
5 Brooks F T, Pope D S, Marcolini M A. Airfoil Self Noise and Prediction. Washington, D C: NASA Reference Publication, 1989
6 Lowson M V. Assessment and prediction model for wind turbine noise: 1. Basic aerodynamic and acoustic models. Flow Solution Report. Bristol: Flow Solutions Ltd., 1993, 93/06, 1–46
7 Oerlemans S, Fisher M, Maeder T, et al. Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations. AIAA J, 2009, 47: 1470–1481
8 Giguere P, Selig M S, Tangler J L. Blade design trade-offs using low-lift airfoils for stall regulated HAWTs. ASME/AIAA Wind Energy Symposium, Reno, Nevada, USA, 1999
9 Frank B, Sørensen N, Johansen J, et al. Risø-R-1280, wind turbine airfoil catalogue. Risø National Laboratory, Roskilde, Denmark, 2001
10 Migliore P, Oerlemans S. Wind tunnel aeroacoustic test of six airfoils for use on small wind turbines. ASME, 2004, 126: 974–985
11 Bak C, Bertagnolio F, Madsen H A. Design of low noise airfoil with high aerodynamic performance. Proceedings of the Third International Meeting on Wind Turbine Noise, Aalborg, Denmark, 2009
12 Howe M S. Noise produced by a sawtooth trailing edge. J Acoust Soc Am, 1991, 90: 482–487