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**[Extended Abstract for Scientific Sessions]**

**Reduction of Wind Turbine Noise Using Optimized Airfoils**

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**[PURPOSE OF THE PRESENTATION]**

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 important as noise is spreading more adverse effect of wind turbine to public. This work demonstrates the design of 10 kW class wind turbines, each of three blades, a rotor diameter 6.4 m, a rated rotating speed 200 rpm and a rated wind speed 10 m/s. The objectives in the design process are to reduce noise emission, while sustaining high aerodynamic efficiency.

## [TEXT OF ABSTRACT]

### I. SCOPE OF THE WORK

Wind power has been come into footlight 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. For those researches, aerodynamic noise from the blades is generally considered to be the dominant noise source, provided that mechanical noise is adequately reduced. 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. 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. Airfoil self-noise is mainly associated with the laminar or turbulent boundary layer on the blade surfaces. This type of noise can has tonal or broadband characteristics, and considered to be caused by several mechanics, such and trailing edge noise, laminar boundary layer vortex shedding noise, tip noise, separated or stalled flow noise, and blunt-trailing-edge noise.

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 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.

### II. METHOD FOR AIRFOIL DESIGN

The airfoil design of wind turbine blades consist 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.

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 which are coupled with the flow solver X-FOIL, which is a panel code with viscous interaction, and the noise solver NAFNOISE which is a semi-empirical code composed of Lawson's equation for turbulence inflow noise, and 2D empirical formulas of Brooks et al. for airfoil self noise.

### A. Design strategy

For airfoil design stage, the design variables are the control points that describe the airfoil shape. In this case, there are twelve design variables which form the airfoil shapes - six 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.

### B. Flow analysis

Flow calculations during the optimization were conducted using X-FOIL. For a given  $Re$ , Mach number, and 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.

**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

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. 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. 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. According to the results of paper survey, the baseline airfoil is selected to be located at 75% spanwise directional position. Consequently, the new optimized airfoil were 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.

### C. Noise analysis

Early researchers, e.g. Brooks et al. divide 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,  $\delta^*$ , 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 on both the suction and pressure side of the airfoil. The total sound pressure level is given as follows:

$$SPL_{total} = 10 \log \left( 10^{SPL_p/10} + 10^{SPL_s/10} + 10^{SPL_\alpha/10} \right) \quad (1)$$

$$SPL_p = 10 \log \left( \frac{\delta_p^* M^5 L D_h}{r_e^2} \right) + A \left( \frac{St_p}{St_1} \right) + (K_1 - 3) + \Delta K_1 \quad (2)$$

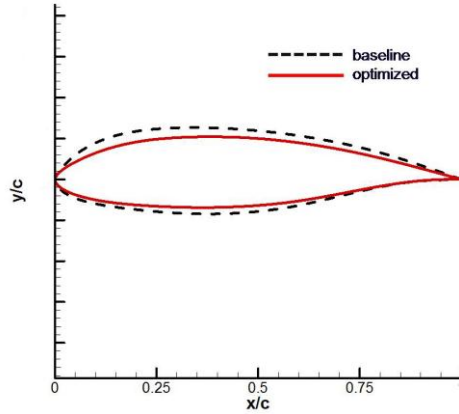
$$SPL_s = 10 \log \left( \frac{\delta_s^* M^5 L D_h}{r_e^2} \right) + A \left( \frac{St_s}{St_1} \right) + (K_1 - 3) \quad (3)$$

$$SPL_\alpha = 10 \log \left( \frac{\delta_s^* M^5 L D_h}{r_e^2} \right) + B \left( \frac{St_s}{St_2} \right) + K_2 \quad (4)$$

Another source of airfoil self noise is vortex shedding from a blunt trailing edge. This noise source will dominate the total 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:

$$SPL_{TEB-VS} = 10 \log \left( \frac{\delta_p^* M^5 L D_h}{r_e^2} \right) + G_4 \left( \frac{h}{\delta_{avg}^*}, \Psi \right) + G_5 \left( \frac{h}{\delta_{avg}^*}, \Psi, \frac{St''}{S_{peak}''} \right) \quad (5)$$

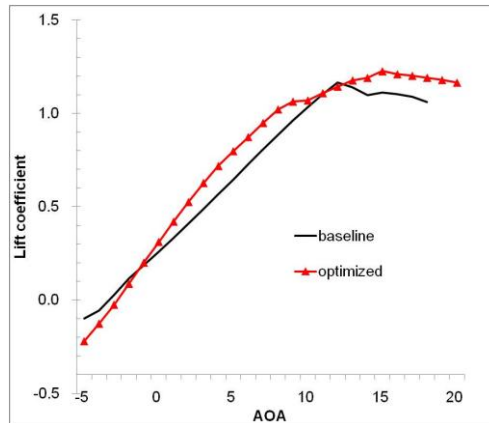
Turbulent boundary layer trailing edge noise is generally considered the most important source of airfoil self noise for modern wind turbine blades of high-frequency noise and is broadband. This is the reason for focusing on this source. Using these results of noise analysis, the airfoil shape is redesigned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



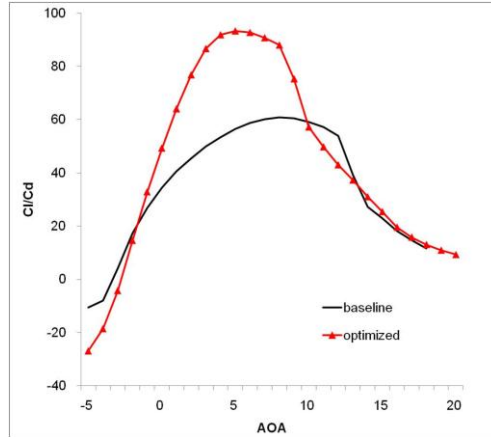
**Fig.1** Airfoil geometry comparison (baseline and optimized airfoil)

### III. 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 thickness of 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 respect to the chord length, respectively. Figure 2 and 3 shows 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,  $7^\circ$ , and improved by 51% in comparison with that of baseline for  $Re = 1.02 \times 10^6$ . These results are satisfied with the desired aerodynamic performances.

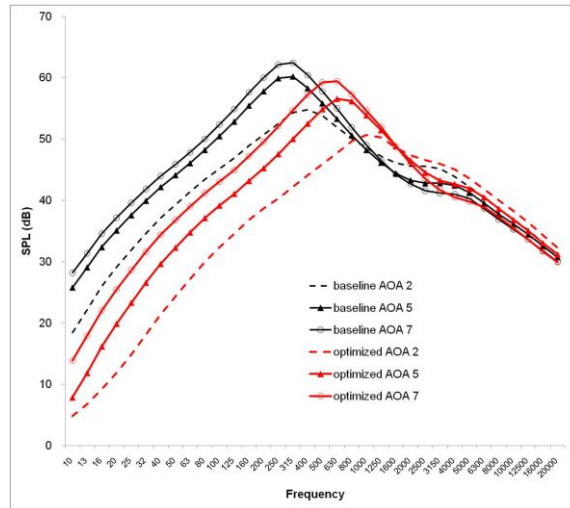


**Fig.2** Lift coefficients for baseline and optimized airfoil



**Fig.3** Lift to drag ratios 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 is more appropriate than noise levels with A-weighted scale because the detectable amount of noise reduction with A-weighting is very weak.



**Fig.4** SPL spectra for baseline and optimized airfoil

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 2,500 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 are the important parameters describing the boundary-layer turbulence. In the higher frequency range above 5,000 Hz, the integrated spectrum for 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 showed that the exact 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 the overall SPL reduction of the optimized airfoil at an angle of attack  $7^\circ$  is 2.9 dB. Thus, the results 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.

#### **IV. CONCLUSIONS**

Airfoil low noise design optimization were 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 were 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,  $7^\circ$ , 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 2,500 Hz ranges and the overall SPL reduction of the optimized airfoil at the design angle of attack is 2.9 dB.