DESIGN OPTIMIZATION OF AIRFOIL FOR WIND TURBINE WITH RESPECT TO ICE ACCRETION

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Abstract

As the demand for wind turbines increases, many wind farms are constructed in the shore and alpine regions in which icing frequently occurs. When ice accretion occurs on a wind turbine blade, performance is hindered, which adversely affects the overall energy generation efficiency. In order to solve this problem, optimization of the wind turbine for the icing condition is carried out. For the primary airfoil NREL 5MW reference wind turbine, the airfoil was optimized with the aim of minimizing the performance-reduction, and it is only applied to 80% radius of the blade section. This study shows that the baseline wind turbine and the optimized blade produced almost the same power in normal condition. Ice-accreted baseline turbine power performance decreased by 4.8% while the optimized turbine blade had a reduction of 3.5%. The result indicates that in the case of wind turbines where icing occurs frequently in same weather condition, optimization of the primary airfoil can improve total power generation efficiency.

1 Introduction

In order to cope with current population growth and increasing coercion on sustainability of our planet, demand for renewable energy source such as the wind power is increasing. As a result, increasing number of the wind turbines are installed on the shore or alpine regions where the temperature is low, the density of the air is high, and the wind often blows. Wind turbines installed in these areas, however, are often be exposed to the conditions that cause ice accretion. Icing conditions occur frequently in the coastal and alpine regions of the Northwest US, Alaska, Greenland, or western Europe when clouds or fogs occur at low altitudes which is known as supercooled fog weather condition [1]. The wind turbine blade shape change when ice accretion occurs, which affects the aerodynamic performances. If the ice condition continues, the power generation efficiency is drastically deteriorated in addition to the structural problem of the blade due to the mass of the ice, as well as the safety concerns of the ice shedding. Various form of deicing mechanisms have been applied especially on the fixed-wing aircraft or rotorcraft. However, deicing mechanisms are reluctantly used for the wind turbine due to the high energy consumption of the heating device. According to a study by Makkonen and Autti [2], if an anti-icing system with a heating device is used for a 100 kW turbine, at least 25% of the maximum power output is required, and more energy may be required if a de-icing devices which rapidly heat the blade is utilized. Essentially, wind turbine without de/anti icing mechanism is desired. Therefore, it is necessary to design the airfoils which minimizes the performance degradation when exposed to the icing environment. Furthermore, it is necessary to study airfoil parameters that affect the aerodynamic performance after the icing occurs.

Researchers have studied to analyze the shape and performance of wind turbines with icing, and design suitable blades for icing condition. Fu [3] investigated the shape change of the wind turbine blades and the amount of ice accreted by the two-phase CFD analysis and the rime ice approach. Switchenko [4] compared ice accretion shapes of 3D icing simulation and 2D sectional icing analysis. The usage of 2D sectional icing approach is justified instead of 3D simulation which is computationally time-consuming. Homola [5] studied the change of power generation performance of NREL 5MW reference wind turbine before and after the icing by blade element momentum (BEM) theory and 2D sectional approach. This study only calculates the power generation, and not the blade design. Yirtici [6] also calculated power generation performance by the BEM theory and the 2D icing shape by sections and showed there was an airfoil shape that could decrease the performance reduction by slightly change airfoil using the bump function. However, there is a limitation due to lack of parameters defining the shape of an airfoil.

In this study, the airfoil for the icing condition is investigated, in order to minimize the aerodynamic performance degradation while the performance of clean airfoil is maintained. The effect of airfoil design parameters such as thickness and camber on the aerodynamic performance was analyzed. The optimized airfoil is applied to the 80% radius section of baseline wind turbine and with this, power generation performance prediction is conducted. The baseline airfoil is NACA64_A17 which is the primary airfoil of the NREL 5MW reference turbine [7].

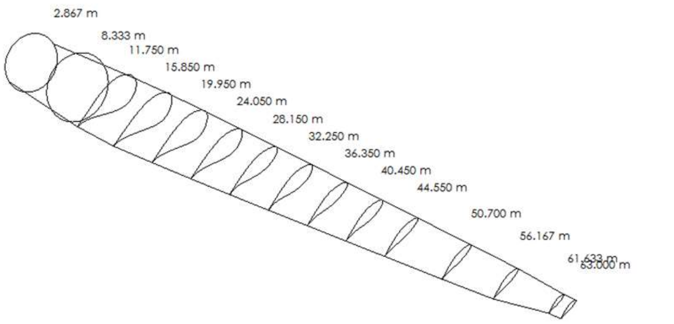

Figure 1 NREL 5MW wind turbine blade and sectional shapes

2 Methodology

In this study, the NREL Reference 5MW wind turbine [7] is selected as the baseline. This wind power generator is a typical modern wind power generator with a radius of 63m and applies pitch and torque control when the wind speed changes.

The airfoil at the 80% blade-radius section is optimized which generates most of the power capacity of the wind turbine. NACA64_A17, an 80% span primary airfoil, was approximated using the PARSEC parameter. The results are shown in figure 3. Using the parameter of the baseline airfoil, the design space was set as at ± 20% of the baseline PARSEC parameters. The design of experiment (DOE) consists of 100 experimental points using the latin hypercube sampling method. The flow conditions at 80% radius section are obtained by using the Blade Element Momentum (BEM) method such as flow velocity and angle of attack (AOA) at the 80% blade section. Afterward, the icing simulation conducted at the flow condition. The airfoil performance is analyzed using panel method before and after the icing. Then, a surrogate model was constructed through the kriging model, and a genetic algorithm(GA) was used to search for the optimal solution. Details are described below.

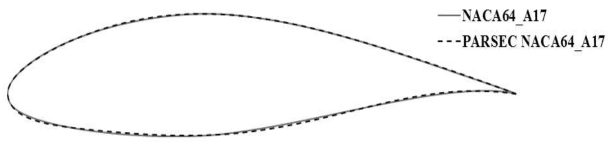

Figure 2 NACA64_A17 airfoil comparison

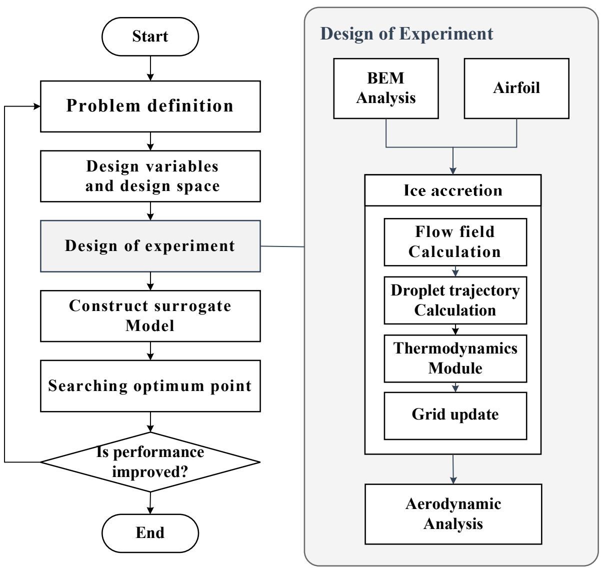

Figure 3 Flow chart of the optimization framework

2.1 Blade sectional shape definition

PARSEC parameter was used to define the shape of the airfoil. As shown in figure 2, eleven variables are used to define an airfoil. In this paper, nine parameters are selected except ΔZte which defines finite trailing edge and Zte which defines the height of trailing edge.

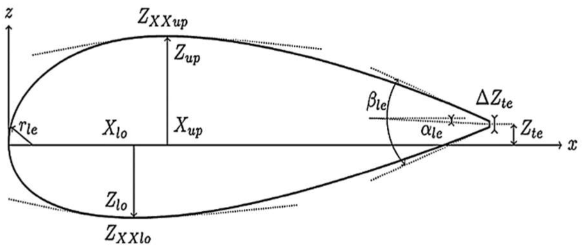

Figure 4 PASEC parameter definition [9]

2.2 Airfoil ice accretion simulation

Ice accretion occurs when supercooled droplet particles hit the surface of the airfoil. The types of ice are classified into rime ice and glaze ice. The icing shape can be differentiated according to the atmospheric temperature, free stream velocity, Liquid Water Content (LWC), Median Volume Diameter (MVD), and exposure time. The icing shape prediction is performed assuming quasi-steady state. The 2D ice accretion is simulated through the following processes. First, the flow field is calculated using doublet panel method. Second, droplet trajectory is calculated by the lagrangian approach. The gravity, drag, and buoyancy force determine the amount of impinging water at the surface of an airfoil. Third, the mass conservation and energy conservation equation are applied using messenger model to determine freezing fraction and runback water. Finally, the mesh moves as much as ice. The code was verified in Ref.10 as compared to the icing shape of the icing wind tunnel test.

In this study, the icing simulation conditions such as MVD, LWC, temperature, and free stream velocity are selected according to the supercooled fog weather condition, which is known to occur frequently in the coastal and alpine regions of the Northwest US, Alaska, Greenland, or western Europe. The values are presented in table 1. The sectional flow conditions are determined at the 80% blade-radius section, which is calculated by the BEM method.

Table 1 ice accretion simulation conditions

Ambient temperature	-10℃
Free-stream velocity	10m/s
LWC	0.1g/m^3
MVD	35μm
Exposure time	2 hr
Ambient pressure	1000hpa
Humidity	100%

2.3 Airfoil aerodynamic force analysis

2D airfoil aerodynamic performance analysis was carried out using XFOIL which is a panel-based flow analyzer developed by MIT. It performs boundary layer compensation, transition point prediction, and correction of viscous effects [11]. The XFOIL results are relatively accurate in the pre-stall linear region. AOA of the primary airfoil of baseline wind turbine is to be in pre-stall region. Also, XFOIL is time very efficient. Therefore, it is appropriate to be used design optimization in this paper in terms of efficiency and accuracy.

2.4 Wind turbine performance analysis

QBlade is an analyzing and designing tool for a wind turbine, which is publically distributed under the GNU Public License [12]. The performance of wind turbine blade is predicted using BEM analysis tool of QBlade. BEM is a widely used method for predicting or designing the performance of wind turbines. It calculates the blade performance by dividing the span into finite elements and using the aerodynamic analysis value of the 2D section. The aerodynamic coefficients of the turbine such as power and trust coefficients are calculated by introducing the axial induction factor and the angular induction factor. The axial induction factor represents the flow through the rotor disc, and the angular induction factor represents the rotation of the flow. The Prandtl tip loss function was exploited to account for the tip loss effect. In figure 6, , the obtained performance of the NREL 5 MW reference wind turbine with the current BEM method and the data in Ref.7 are compared. In general, the data corresponded well.

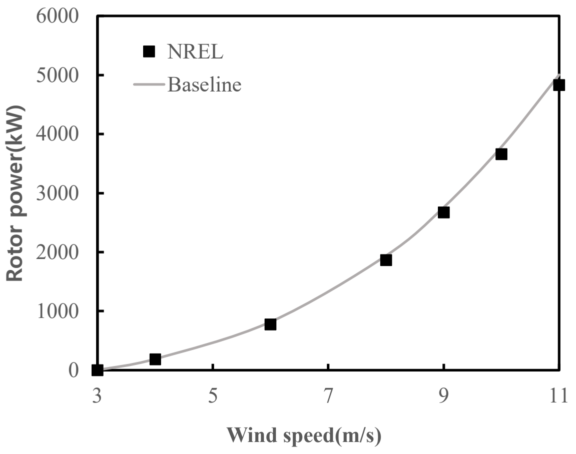

Figure 5 Rotor power for baseline wind turbine

2.5 Optimization process

To optimize the shape of the blade section, a surrogate model was used. With surrogate model, kriging model is selected, which is known to be effective for expressing nonlinear responses.. For the design of experiment method, latin hypercube sampling was used to determine the experimental points for constructing the kriging model.

Genetic algorithm(GA) was also used to find optimal point. GA is applied for optimization of natural evolution and natural genetic inheritance. Since the genetic algorithm does not use the slope information of the objective function, there is a high possibility of finding a global optimal point even for a problem having a large nonlinearity.

3 Design optimization problem definition

The parameter defining the airfoil shape was set based on ± 20% of PARSEC parameter of the baseline NACA64_A17, and the 100 experimental point was constructed using the latin hypercube sampling technique.

When icing occurs, lift coefficient decreases and drag coefficient increases [1]. Therefore, the objective function used L/D and the change of the L/D ratio before and after the ice accretion, optimizes the aerodynamic performance by simultaneously considering lift and drag. Each variable is defined as follows.

$$\text{Objectives: Maximize } L/D_{clean} \quad \text{Minimize } \Delta L/D \tag{1}$$

$$\Delta L/D = \frac{L/D_{clean} - L/D_{iced}}{L/D_{clean}} \tag{2}$$

4 Result and discussion

The pareto line of the objective functions obtained using Kriging and GA is shown in the figure 6. The points depicts an optimum airfoil design. The point at the upper left corner indicates insensitivity of the aerodynamic performance to icing shape change. The point at the lower right corner indicates aerodynamic performance is good before icing. After the ice accretion occur, however, the performance drastically decreased. The two points which are represented by Opt1 and Opt2 are examined. The Opt1 is the point that the performance is similar before icing but the performance reduction is relatively small after icing. The Opt2 is the airfoil which performs better when it is clean but the performance degradation is similar to baseline airfoil when ice accretion occurs.

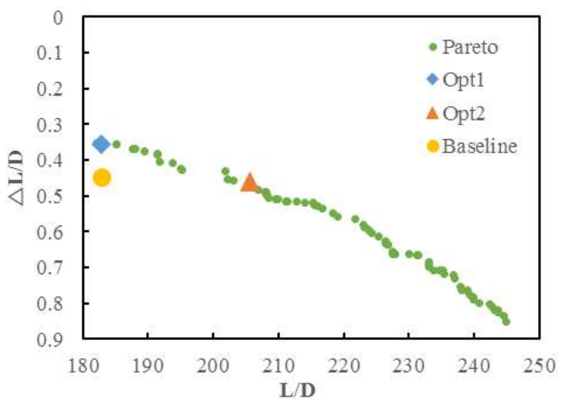

Figure 6 Objective functions pareto line

Table 2 Airfoil parameters of optimum points

	Baseline (NACA64_A17)	Opt1	Opt2
Thickness(%)	18.0	17.0	17.3
Thickness location(%)	36.8	36.4	35.2
Camber(%)	3.04	4.24	4.66
Camber location(%)	54.2	63.9	63.9

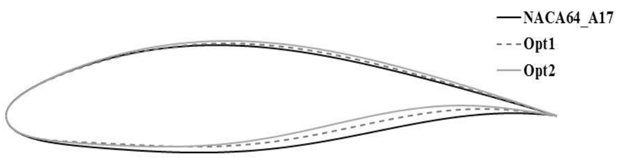

Figure 7 Airfoil of optimum points

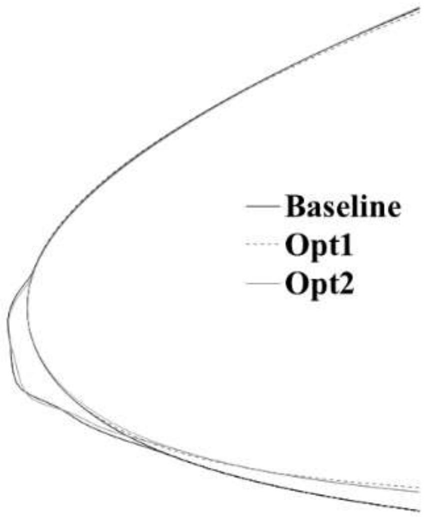

Figure 8 Ice shape of the airfoils

The baseline, Opt1, and Opt2 airfoils are shown in figure 7. Also, the airfoil shapes of leading edge (10% chord) after the ice accretion are presented in figure 8. The optimized geometries Opt1 and Opt2 all show that the pressure side near the trailing edge is lowered which translates to larger and backward cambers than the baseline airfoil. This is because the icing shape causes the droop of the airfoil at the leading edge, making the effective camber small and making the lift force small. The airfoil shape then enlarges and enlarges the camber at the back to keep up the lift force. In addition, the thickness of optimized geometries is smaller than baseline thickness, which can reduce the thickness of the boundary layer to make the drag smaller.

Even if the airfoil is optimized, the icing shape itself does not show a large difference as shown in figure 8. This means that the performance difference by changing icing shape cannot be improved unless the airfoil shape is largely changed.

Considering design of the wind turbine, the power production is one of the most important factors. Therefore, the power production performance calculations of the baseline blade and the blade whcih is applied optimum airfoil(Opt1) at 80% radius section are carried out before and after ice accretion. At first, ice simulation is conducted. Figure 9 shows the shape of the baseline blade after it is exposed icing condition. Five sections from 58% radius to 98% radius is applied.

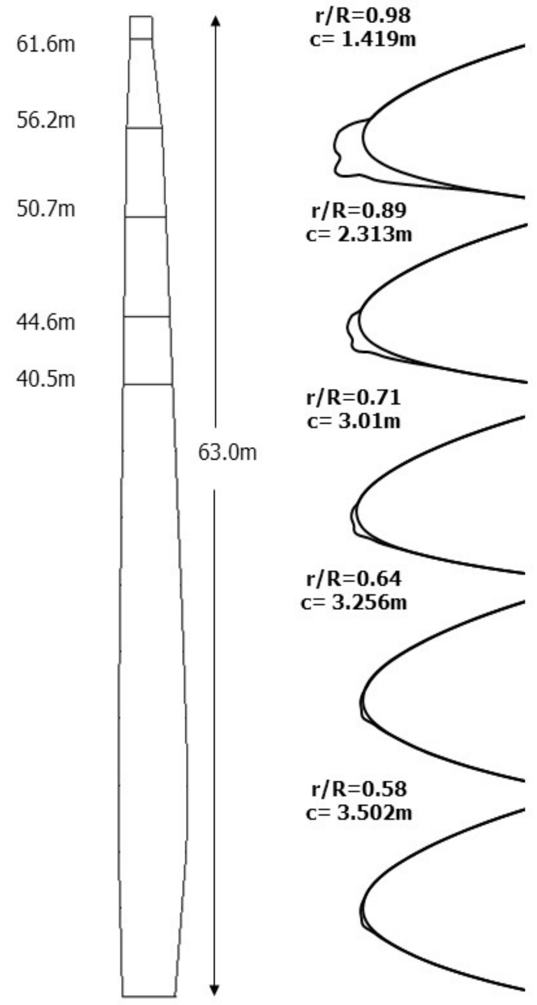

Figure 9 Baseline blade after ice accretion

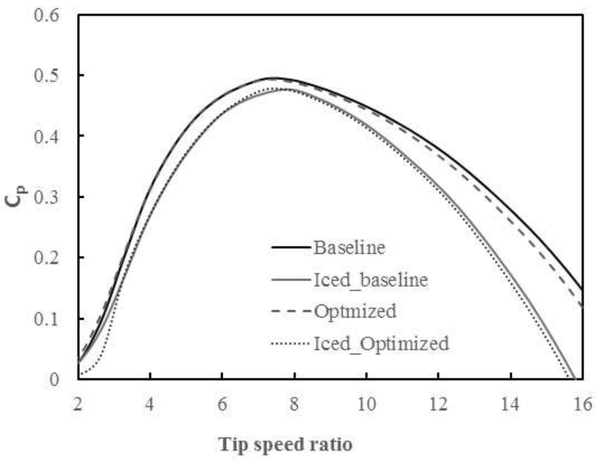

Figure 10 Power coefficient versus tip speed ratio curve

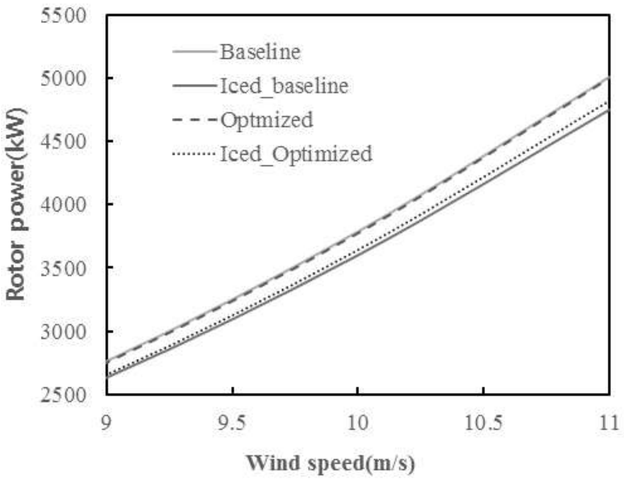

Figure 11 Power production at target wind speed

Figure 10 shows the power coefficient versus tip speed ratio of the baseline wind turbine and optimized wind turbine before and after ice accretion. The optimized wind turbine means that optimum airfoil is applied at 80% radius section of the baseline wind turbine. The power coefficient near the tip speed ratio of 6 to 8, which is target tip speed ratio, slightly increased after optimized airfoil is applied. However, in the other region, the power coefficient is degraded, which means the optimized blade is lower performance than baseline blade. The power generation capacity near the target wind speed where the velocity of the free stream is 10m / s is calculated as shown in figure 11. The same control conditions were applied to the baseline turbines using the NREL report data [7]. At 10m/s, the baseline wind turbine produced 3784kW, and the iced baseline wind turbine produces 3602kW, which reduce the generation capacity by 4.8%. However, in the optimized wind turbine, Rotor power is 3777kW and decreased by 3.5% to 3642kW when the icing occurred. This result means the wind turbine design procedure which the optimizing primary airfoil is effective. If optimized airfoil is applied to the turbine blade, it can reduce the performance degradation after icing while maintaining the performance when the blade is clean. This means that it can have a good influence on the AEP in the region where the target icing environment is frequent.

4 Conclusion and future work

Design optimization for NACA64_A17, which is used as primary airfoil in NREL 5MW reference wind turbine, is performed to minimize performance degradation after icing. It is obtained the optimal airfoil that minimizes the performance(lift to drag ratio) degradation after icing in frequent icing conditions. The optimized airfoils show a shape with thinner thickness and, larger and backward camber than baseline airfoil due to the lowered pressure side height near trailing edge. The optimized airfoil is applied to the baseline wind turbine blade at 80% radius section and the performance is predicted. The power coefficient of optimized blade is similar to baseline before icing and slightly higher than baseline after shape change due to icing. In addition, the rotor power generation is calculated in the target velocity region. It is predicted that the performance decrease was 4.8% in the case of baseline wind turbine and 3.5% in the case of optimized turbine. This means that in case of wind turbines where icing frequently occurs in a weather condition, it is possible to improve the power generation efficiency by optimizing only the primary airfoil.

Since the aerodynamic analysis is based on the panel method, there are limitations in lift and drag prediction. Therefore, the CFD analysis will be conducted to increase accuracy. Also, the airfoil designed under certain conditions may not be the optimal point in the other condition since the icing shape changes when the icing occurs in other weather conditions. For example, when the glaze ice upper horn shape appears at the leading edge, effective camber can be increased. Then, the optimal shape might have the smaller camber than baseline airfoil. Therefore, it is desirable to optimize airfoil in various weather conditions.

Acknowledgements

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