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Study on influence of blade icing on operational characteristics of wind turbine at cold climate

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Abstract. In this paper, the icing effect on wind turbine is investigated. The sectional aerodynamic performance of iced blade was measured in wind tunnel with icing airfoil models. The analysis conducted by using FAST using the measured sectional performance was conducted to investigate the degradation in wind turbine performance and added load due to icing. Frequency analysis was also conducted with the time series data calculated by using FAST. As the results, the power output at the rated wind speed for the icing case is smaller than that for the clean case and the maximum rotor thrust for the icing case is smaller than the clean case. The wind speed at which the turbine's rated power is reached for the icing case was higher than that for the clean case.

1. Introduction

The wind turbines at cold climate which operate in high latitude area are frequently facing icing conditions. Recently, the wind energy installations at cold climate growth rapidly in high latitude area due to the high air density, and also the wind turbines are easy to accept due to the low population density. However, it has the problem of icing on the wind turbines. Icing is a phenomenon in which "supercooled water droplets" in the atmosphere collide with an object and freeze it. It is thought that the most significant effect of the icing event on the wind turbine is blade ice accretion. Thus, in order to operate the wind turbines in cold regions, it is necessary to take measures that anticipate icing. Seifert et al.[1] made four kinds of icing models observed in the ice cross-section on the blade, and conducted the two-dimensional airfoil performance test in the wind tunnel. From these airfoil performance data, a power curve diagram of 300kW wind turbine was estimated. By using FAST analysis, V. Lehtomäki et al.[2] evaluated the change in blade aerodynamic load due to icing and the effects on fatigue load due to increased mass due to icing. It was obvious that fatigue load due to changes in blade aerodynamic loading, the low speed shaft and the tower was larger than that due to increased mass. IEA Wind proposes a T19 Ice loss Method[3] that predicts icing from the power output curve, utilizing the fact that the power output of the wind turbine decreases due to the reduction of the airfoil performance for the icing. In addition to such a system to detect the icing, it is necessary to establish the most reliable and safe wind turbine operational method in cold region.

The issue of wind turbine operation in cold region is the change in aerodynamic load due to icing. The risk of ice falling and throwing should be also given most attention. Therefore, it is necessary to operate wind turbine with blade icing safely and efficiently. And it is required to set appropriate wind

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turbine operation limits in cold climates. This study evaluates the impact of icing blade on the operation of wind turbines and demonstrates detection of the blade icing by performance and/or load.

2. Experimental setup and analysis procedure

2.1 Airfoil sectional performance test

Figure 1 shows a side view of the wind tunnel for airfoil sectional performance test. The wind tunnel is a low turbulence closed-circuit type wind tunnel with the outlet area of 650×650 mm², the maximum wind speed of 55 m/s and the turbulence intensity of 0.28 %. The aerodynamic forces of airfoil were measured by a three-component balance system. The attack angle of airfoil is set by a servo motor system.

Figure 2 shows experimental setup for balance measurements. The three-component balance supports the airfoil model and measures a stream-wise force (F_x) , a normal force to the flow (F_y) , and a moment around quarter chord axis (M_z) .

Figure 3 shows the cross-section of two test airfoils, r7000 and r12500. The test airfoils are twodimensional sectional models of the target wind turbine blade. The span-wise location of r7000 airfoil is 7 m and that of r12500 airfoil is 12.5 m.

Figure 4 shows the icing models attached to the leading edge of airfoil. In this paper, the icing model is simplified even though the shape of actual icing is complex shape. The icing models in this paper were defined as $R1^+$, $R3^+$ and $R5^+$ with increasing icing length. In this paper, $R1^+$, $R3^+$ and $R5^+$ is called the icing class [4][5].

The surface roughness is reproduced by attaching sandpaper to the surface of airfoil model. The surface roughness caused by icing was calculated using LEWICE[6]. LEWICE is a code for calculating the icing object shape of a two-dimensional airfoil such as an aircraft in time series, and it is necessary to input weather conditions such as the wind speed flowing into the airfoil and the median diameter of water droplets in the air. Thus, the process of icing can be reproduced by evaluating the collision characteristics among the flow around the airfoil, the droplet, and the heat transfer from the airfoil surface. LEWICE defines empirical formulas for calculating the surface roughness of icing objects. In this formula, surface roughness is expressed as sand grain roughness. And it is determined by inflow wind speed, air temperature, LWC (liquid water content), MVD (median volume diameter), and chord length, where LWC $[g/m^3]$ is the mass of water droplets contained in 1 m³ of air, and MVD $[\mu m]$ is the volume median diameter of the water droplets.

In addition, the sandpaper used for wind tunnel experiments was selected by calculating the averaged diameter of the sandpaper particle from the particle size distribution of abrasives for JIS R 6010 2000 abrasive cloth paper [7]. Table 1 shows the size of the icing model and the surface roughness, and the roughness of the sandpaper. Figure 5 shows the coarse diameter k_s on the rough sand surface.

2.2 Wind turbine simulation

The analyses of power output and load are conducted by using FAST code [8]. The measured airfoil sectional performance data are used for the blade input data of FAST. Table 2 shows the specifications of the target wind turbine. In the simulation, turbulent wind was used. The averaged inflow wind speed is 17.5 m/s, which maintains the rated power output by pitch angle control under assumption of air temperature of 10 °C. The analysis results of the blade root moment are shown in this paper.

2.3 Frequency analysis

The frequency analysis was conducted by FFT with the time series data obtained by using FAST. The vibration of the blade and the tower are evaluated. The amplitudes of the edgewise moment and the flap-wise moment at the blade root of the target wind turbine were evaluated.

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Icing airfoil model			r7000	r12500	
		$R1^+$	0.6	2.7	
Icing length[mm]	Ice class	Ice class	R3 ⁺	2.1	8.5
		$R5^+$	6.2	22.4	
Surface roughness ks[mm]			0.12	0.15	
Sandpaper Roughness			P120	P150	

Table 1. Icing model and surface roughness

Table 2. Specifications of wind turbine

Target wind turbine	Up-wind type HAWT		
Rated power output	300 kW		
Rotor diameter	33 m		
Rated speed	40.5 min ⁻¹		
Rated wind speed	11.5 m/s		
Cut-in wind speed	3.0 m/s		
Cut-out wind speed	25.0 m/s		
Optimal tip speed ratio	7.5		
Output power control	Pitch angle & variable speed control		



Figure 1. Side view of wind tunnel

Figure 2. Experimental setup for balance measurements



Figure 3. Cross-sections of test airfoil



Figure 4. Icing model at leading edge of airfoil

Figure 5. The sand grain roughness k_s on the rough sand surface

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3. Results and discussion

3.1. Experimental results

Figure 6 shows the measured lift coefficient C_L for r7000 with various icing conditions. The test Reynolds number is 3.0×10^5 . The horizontal axis shows the angle of attack α and the vertical axis show the lift coefficients C_L . The lift coefficient for the clean shows linear increase with increasing angle of attack in the range $-9 < \alpha [^0] < 12$. The width of the liner range becomes smaller in the order of clean, R1+, R3+ and R5+. The C_L for both clean and icing is the same for same angle of attack in the linear region. Table 3 shows maximum lift coefficient and stall angle for the clean and icing. From table 3, the maximum lift coefficient for the icing is smaller than that for the clean. The maximum lift coefficient of airfoil for low Reynolds number becomes larger with increasing the curvature of the leading edge and smaller with increasing chord length [9]. It is thought that the larger the curvature of the leading edge, reattaching of the laminar separation bubbles generated at the leading edge are maintained at high angles of attack, and the larger the chord length at high angles of attack causes the separation on the suction surface. It is considered that the maximum lift coefficient for the icing was reduced because the icing model on the leading edge is reduced the curvature of the leading edge.

Figure 7 shows the drag coefficients C_D for r7000. The horizontal axis shows the angle of attack α and the vertical axis show the drag coefficients C_D . From figure 7, it can be seen that the drag coefficient for the icing is higher than that for the clean at the angle of attack above linear portion of lift coefficient in each icing class. In the angle of attack range of linear portion of lift for the icing, the C_D show roughly similar value for the icing and the clean. Therefore, it can be seen that there is almost no effect of icing in this linear portion.



Table 3. Maximum lift coefficient and stall angle

Figure 6. Lift coefficient curve

Figure 7. Drag coefficient curve

Figure 8 shows the lift coefficient C_L for r12500. The test Reynolds number is 3.0×10^5 . The horizontal axis shows the angle of attack α and the vertical axis show the lift coefficients C_L . In the linear portion of lift coefficient, the slope for the icing is smaller than for the clean. The lift-curve slope increases with increase in thickness [10]. This is because the larger thickness, the larger leading edge radius provide an easily detour of the airflow to the suction surface. On the other hand, a smaller leading edge radius makes it difficult, the airflow easily separates on the suction surface at a high angle of attack. The airfoil

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thickness of r12500 is smaller than that of r7000. The chord length increase of r12500 by icing is larger than that of r7000. It can be seen that the relative thickness of the icing, including the icing, is smaller than that of the clean. It is considered that the lift slope for the icing become small. The lift coefficient near $C_L = 0$ have less effect of icing, is almost the same as the clean one.



Figure 8. Lift coefficient curve

3.2. Wind turbine performance

The power and thrust is calculated by using FAST at the inflow wind speed of 11.5 m/s, which is the rated wind speed of the target wind turbine.

Figure 9 shows the power coefficient C_P against the tip speed ratio λ . From figure 9, the maximum power coefficient for the clean is 0.474. And the maximum power coefficient for the icing is smaller than that for the clean. Thus, the icing reduces the maximum power coefficient. Below optimum tip speed ratio, the power coefficient increases with the increase of the tip speed ratio, and the power coefficient increases in the order of the icing classes R5⁺, R1⁺ and R3⁺.

Table 4 shows the maximum power coefficient and the optimum tip speed ratio for each icing model. From table 4, the optimum tip speed ratio shifts to the higher tip speed ratio for the icing condition. This is considered that by icing, shifting to the high tip speed ratio is affected by the small lift coefficient for blade section close to tip. It is considered that the angle of attack for the maximum power coefficient is changed by decreasing lift and increasing drag due to icing.

Figure 10 shows the thrust coefficient C_T of the target wind turbine. The horizontal axis shows the tip speed ratio λ and the vertical axis shows the thrust coefficients C_T . From figure 10, the thrust coefficient under the icing conditions is smaller than that for the clean in the range of $\lambda < 8$. It was considered that the lift coefficient for the icing is lower than that for the clean at the same λ by smaller lift slope for the icing. For $\lambda > 10$, the C_T for the icing is larger than that for the clean. However, the wind turbine operation with higher λ happens under the decreasing wind speed condition, so it seems to have no effect on the blade load.

Tat	ole	4.	Μ	laxımum	power	coefficient	and	optimum	tıp	speed	ratio
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	clean	R1 ⁺	R3 ⁺	R5 ⁺
Maximum Power Coefficient	0.474	0.468	0.473	0.447
Optimum Tip Speed Ratio	6.76	8.26	8.26	7.51



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Figure 9. Power coefficient curve

Figure 10. Thrust coefficient curve

3.3. Load analysis

Figure 11 shows the edgewise moment at the blade root above rated wind speed of 17.5 m/s. The horizontal axis shows the time and the vertical axis shows the edgewise moment at the blade root. From figure 11, it can be seen that the edgewise moment fluctuates periodically. This is explained as follows. The edgewise moment changes by the edgewise component of aerodynamic force on the blade and also by the load due to the weight of the blade itself including the ice weight whose edgewise component depends on azimuth angle.

Table 5 shows the averaged edgewise moment at the blade root of each icing model at the wind speed of 17.5 m/s. From table 5, the edgewise moment at the blade root under the icing conditions is smaller than that for the clean. This is explained as follows. The aerodynamic force contributing to the edgewise moment close to tip is decreased by decreasing lift under the icing condition.

Table 5. Averaged	l edgewise mome	nt at blade root
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	clean	R1 ⁺	R3+	R5+
Averaged Edgewise Moment	2.95	2.15	2.07	2.16
at Blade Root [kNm]				



Table 6. Averaged flapwise moment at blade root



30 Time [s]

40

50

60

20

Figure 11. Edgewise moment at blade root

10

0

R1⁺

87.0

R3⁺

86.1

R5⁺

88.9

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Figure 12 shows the flapwise moment at the blade root above rated wind speed of 17.5 m/s. The horizontal axis shows the time and the vertical axis shows the flapwise moment. From figure 12, it can be seen that the flapwise moment fluctuates periodically. The angle of attack of the blade element is changed by local wind speed, so the wind shear makes periodical fluctuation.

Table 6 shows the averaged flapwise moment of each icing model at the wind speed of 17.5 m/s. From table 6, the flapwise moment for the icing is slightly larger than that for the clean. Above rated wind speed, the angle of attack of blade element is reduced to maintain the rated power by increasing the blade pitch angle. As a result, although the lift coefficient for the icing is smaller than that for the clean, the flapwise component of the aerodynamic force on the blade element is increased by increasing the chord length due to the icing. Therefore, it is considered that the flapwise moment is increased due to the increase of the icing above rated wind speed.

3.4. Frequency analysis

Figure 13 shows the results of the frequency analysis for the fluctuation of the edgewise moment above rated wind speed of 17.5 m/s. The horizontal axis shows the frequency and the vertical axis show the edgewise moment amplitude. From figure 13, both for the icing and the clean cases, the peak frequency is f = 0.683 [Hz]. It is 1P frequency for this rotor.

Table 7 shows the maximum amplitude of the edgewise moment at the peak frequency at 17.5 m/s of each icing class. The amplitude of the edgewise moment at the blade root is affected by the edgewise component of the aerodynamic force on the blade and also the increase in blade mass due to the icing. From table 7, the amplitude under the icing condition is larger than that for the clean. The fluctuation of the edgewise moment due to aerodynamic force is decreased by setting up the angle of attack low by pitch angle control. Therefore, the contribution of the aerodynamic force to the edgewise moment has been reduced. Thus, the increase of edgewise vibration is affected by increasing mass of blade under the icing condition.

Table 7. Maximu	m amplitude	of edgewise	moment at	blade root

	clean	R1 ⁺	R3+	R5 ⁺
Maximum Amplitude [kNm]	19.6	19.7	19.8	20.4



Table 8. Maximum amplitude of flapwise moment

Figure 13. Edgewise moment amplitude

Figure 14. Flapwise moment amplitude

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Figure 14 shows the results of the frequency analysis for the fluctuation of the flapwise moment above rated wind speed of 17.5 m/s. The horizontal axis shows the frequency and the vertical axis show the flapwise moment amplitude. From figure 14, both for the icing and the clean conditions, the peak frequency is f = 0.667 [Hz].

Table 8 shows the maximum amplitude of the flapwise moment of each icing class at the peak frequency of rotor rotation frequency at 17.5 m/s. Above rated wind speed of 17.5 m/s, the maximum amplitude increases in the order of R5⁺, R1⁺, R3⁺ and clean condition. The amplitude of the flapwise moment is affected by the flapwise component of aerodynamic force on the blade. Under the icing condition, the fluctuation of the angle of attack cause small fluctuation in the lift coefficient with small lift slope. Therefore, the maximum amplitude is smaller under the icing condition than that for the clean. Therefore, it is considered that the amplitude due to the rotation frequency has a large effect on the flapwise moment, and the fatigue load decreases for the icing.

4. Conclusions

In this study, it was clarified the effect of blade icing on wind turbine load. The icing-shape models and the surface roughness are attached on two-dimensional airfoil, and the airfoil sectional performance was conducted in wind tunnel. Furthermore, in order to determine the wind turbine performance under the icing condition, the evaluation was performed by using FAST. Finally, the frequency analysis at blade root using time series data obtained by using FAST. The main results of this study are shown below.

- (1) The maximum lift coefficient under the icing condition is smaller than that for the clean, and the drag coefficient under the icing condition is larger than that for the clean in the non-linear portion of lift coefficient.
- (2) The drag coefficient under the icing condition is almost the same as that for the clean in the linear portion of lift coefficient, regardless of the icing class.
- (3) Under the icing condition, the maximum edgewise moment at the blade root is larger than that for the clean.

The maximum flapwise moment under the icing condition is smaller than that for the clean.

- (4) The edgewise moment amplitude under the icing condition becomes larger than that for the clean. And the amplitude increases as the blade mass increases by the icing.
- (5) The flapwise moment amplitude under the icing condition becomes smaller than that for the clean. And the amplitude decreases due to the small fluctuation of the lift coefficient with small lift slope.

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