A RECIPE TO ESTIMATE AERODYNAMICS AND LOADS ON ICED ROTOR BLADES

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Abstract

Wind tunnel tests have been carried out using "artificial" iced profiles with various types and amount of ice accretion gained from real iced rotor blades. This information has been used as an input for aerodynamic load calculation and power output prediction. Coefficients of lift, drag and aerodynamical moment were measured at the original clean airfoil and with added leading edge ice models in an angle of attack range between -10° to 30° degrees. A recipe has been developed to transfer the wind tunnel test results to any other airfoil used on wind turbine rotor blades and furthermore an extrapolation method is given to predict the behaviour of iced airfoils in the high angle of attack range. Finally, an approach to estimate the aerodynamic and mass loads due to icing and to predict the loss of energy caused by an iced rotor is given.

1 INTRODUCTION

During the operation of wind turbines under icing conditions the leading edge of the rotor blades collect more and more ice around the stagnation point of the airfoils over the radius. Due to the increasing air velocity along the radius, the ice accretion builds up more at the outer part of the blade with an approximately linear increase [1]. With growing ice accretion the drag of the airfoil increases, diminishing the power output of the turbine. It was expected that the larger chord length should also increase the lift at the iced cross section of the blade and thus, increase the bending moments at the blade root [2]. However, the ice at the leading edge obviously diminishes the lift coefficient at a given angle of attack which compensates the effect expected. Due to the growth of chord length at the leading edge the pitching moment increases dramatically which may affect the pitch control mechanism.

In order to enable wind turbine designers to predict aerodynamic loads and energy losses for wind turbines operating under icing conditions it is necessary to qualitatively and quantitatively know the changes in the aerodynamic properties brought about by ice accretion on the blades. The results of the wind tunnel tests carried out using "artificial" iced profiles (see Fig. 1) with various types and amount of ice accretion were used as an input for the procedures described in the following:
2. CATALOGUE OF ICE FRAGMENTS

Pieces of rime ice from the leading edge with its typical cross sections as it is shown in Fig. 2 were collected from various rotor blades under various icing conditions, preserved and catalogued [2],[3].

An amount of artificial leading edge ice accretion in the range of 3 to 44 per cent of the uniced chord length were investigated in the wind tunnel.

Fourteen typical leading edge ice fragments have been catalogued up to now and half of them have been tested in the wind tunnel. For some of the fragments, which are stored in a data base, also the meteorological conditions during the icing events are partly known. The different types of leading edge ice accretion were defined according to their specific influence on drag and lift versus angle of attack behaviour within the measurements.
3. TRANSFORMATION OF WIND TUNNEL RESULTS TO OTHER AIRFOILS

The influences of different ice shapes and sizes were investigated in the wind tunnel of the University of Braunschweig. Coefficients of lift, drag and aerodynamical moment were measured at the original clean airfoil and with added leading edge ice models at a Reynold’s number of 630,000 using direct force measurements in an angle of attack range between -10° to 30° degrees. All coefficients described are defined by the original chord length of the non-iced airfoil, in spite of the larger chord length (larger area) with ice accretion. As a basis airfoil for the measurements a NACA4415 was chosen [3]. Using the original cross section from the blade close to the tip a rectangular wind tunnel model was manufactured with a chord length of 225 mm and a wing span of 500 mm. The ice accretion was modelled by duplicating the fragments found at the original turbines. Fig. 1 shows the position of the model without ice accretion between the end plates fixed by wires in the centre of the open measurement cross section of the wind tunnel with a diameter of 1.3 m. Six load cells measure the forces which are further amplified, stored and evaluated by a data acquisition system. The influence of the wires and the end plates of the wind tunnel model on the measurement were calibrated in a first measurement campaign.

Fig. 3 Aerodynamic coefficients measured at the clean and various iced NACA4415 airfoil in the wind tunnel of the University of Braunschweig [3]

The profile characteristics of the clean and different iced sections are summarised in Fig. 3 for the lift coefficients versus drag coefficients and for lift and aerodynamical moment coefficients versus angles of attack. There is a remarkable difference between the type B with 22 per cent and the type C with 44 per cent ice accretion, respectively. The reason can be seen
in the shape of the ice accretion especially the sharp edged plate of the 44 per cent type. The maximum lift coefficient of this type is higher and the minimum drag coefficient lower, compared against the 22 per cent ice accretion. The method how to transform the measured aerodynamic coefficients from the iced NACA4415 airfoils to any other airfoils is described in the following:

First, the angle of attack ranges have to be defined at both of the airfoils, the new airfoil (index NP) for which the coefficients with ice accretion are searched and the well known iced and uniced NACA4415 (index NACA). Also the stall behaviour of the particular airfoil has to be known and influences the transformation and the extrapolation, respectively. Three basic types of stall are recognised: First, the trailing-edge stall that occurs when the flow begins to separate at the trailing edge, and with increasing angle-of-attack, the separation gradually progresses towards the leading edge (line a in Fig. 4).

This is considered as a gentle type of stall and more desirable than other types, since the lift decreases gradually from its maximum value. Secondly, the leading-edge stall which starts as a short bubble is formed in the vicinity of the leading edge (line b in Fig. 4). When it bursts, a rapid change of flow over the upper surface of the airfoil occurs, resulting in both a sudden drop in lift and an increase in the profile drag. Thirdly, the thin-airfoil stall, which starts with a long "stable" bubble which elongates gradually and eventually bursts (line c in Fig. 4). The type of stall is strongly influenced by the geometry of the front part of the airfoil section.
within 10 to 15 percent from the leading edge; the most important factors being the shape of the mean-line curve between 0 and 15 percent of chord length, and the leading-edge radius. The user of the transformation has to decide, which type of stall occurs for his particular airfoil. In case of a trailing-edge stall, the Viterna’s equation [see 4.] will be used from the stall angle which must be declared before in the program. In case of leading edge stall, which has been the case for the measured NACA 4415 profile, the Viterna’s equation will be used from an angle of attack of 25 degrees.

Basis for the transformation are the zero lift angles of attack $\alpha_o$ and the angles of attack $\alpha_{c_{l,max}}$ at the maximum lift coefficient $c_{l,max}$, respectively:

\[ (1) \quad \alpha_{NACA} = a \cdot \alpha_{NP} + b \quad \text{with} \quad a = \frac{(\alpha_{c_{l,max}} - \alpha_o)_{NACA}}{(\alpha_{c_{l,max}} - \alpha_o)_{NP}} \quad \text{and} \quad b = \alpha_o_{NACA} - a \cdot \alpha_o_{NP} \]

The transformation of the angle of attack of the new airfoil for which the $\Delta c_l$, $\Delta c_d$ and $\Delta c_m$ values are searched at the angle of attack of the clean NACA4415 profile (see Fig. 5). The interpolation of $\Delta c_l$, $\Delta c_d$ and $\Delta c_m$ of the NACA4415 - coefficients for the chosen ice accretion follows. Further the multiplication of the differences with the factor gained from the difference between the maximum lift coefficient of the new airfoil and the NACA4415 airfoil as given in equation (2) has to be carried out:

\[ (2) \quad K_a = \frac{c_{l,max,NP}}{c_{l,max,NACA}} \]

Finally, the differences are added to or subtracted from the related coefficients of the new airfoil. Fig. 6 shows the result of the transformation method described above for a NACA 63-415 airfoil.
4. EXTRAPOLATION TO POST STALL REGION

Most of the aerodynamic codes for calculating loads and power output require high angle of attack values. Depending on the type of the wind tunnel and the type of measuring the aerodynamic coefficients for angles of attack up to 30° in maximum could be assessed. However, the behaviour of an iced airfoil and a flat plate at high angles of attack are comparable. The method described in the following uses Viterna’s approach for the interpolation between the measured curves and the flat plate values, respectively [5].

Fig. 6 Example for an “iced“ NACA 63-415.

Fig. 7 Extrapolated lift and aerodynamical moment coefficients versus angle of attack.
Fig. 7 shows measured and extrapolated values of $c_l$ and $c_m$ for angles of attack up to $40^\circ$. The measured and interpolated flat plate data are marked differently. The following equations (3) to (7) explain the approach to the final curves. As can be seen in equations (3) and (4) the values for the maximum $c_d$ at $\alpha = 90^\circ$ are dependent on the amount of the leading edge ice accretion and the taper ratio of the blade.

(3) \[ C_{d_{\text{max}}} = C_{d_{\text{plate, } \alpha=90^\circ}} \cdot (1 + \frac{t_{\text{ice}}}{t}) \]

For blades with high to infinite taper ratio $\lambda_b$:

(4) \[ C_{d_{\text{max}}} = 2 \cdot (1 + \frac{t_{\text{ice}}}{t}) \]

According to Viterna’s method as described in [5] $c_d$ versus $\alpha$ is given as:

(5) \[ C_d = C_{d_{\text{max}}} \cdot \sin^2 \alpha + B_2 \cdot \cos \alpha \quad \text{with} \quad B_2 = \frac{C_{d_{\text{ref}}} - C_{d_{\text{max}}} \cdot \sin^2 \alpha_{\text{ref}}}{\cos \alpha_{\text{ref}}} \]

(6) \[ C_i = \frac{C_{d_{\text{max}}}}{2} \cdot \sin 2\alpha + A_2 \cdot \frac{\cos^2 \alpha}{\sin \alpha} \quad \text{with} \quad A_2 = \left( C_{i_{\text{ref}}} - C_{d_{\text{max}}} \cdot \sin \alpha_{\text{ref}} \cdot \cos \alpha_{\text{ref}} \right) \frac{\sin \alpha_{\text{ref}}}{\cos^2 \alpha_{\text{ref}}} \]

The coefficient of the aerodynamical moment is further given with the following interpolation procedure between the highest measured angle of attack $\alpha_{\text{ref}}$ and the flat plate simulation, whereas $\alpha_{\text{ref}}$ should be a value in the post stall region. The leading edge ice accretion is covered by the changed aerodynamic coefficients in equation (5) and (6).

(7) \[ C_m = C_{m_0} - x \cdot C_n \quad \text{with} \quad C_n = C_i \cdot \cos \alpha + C_d \cdot \sin \alpha \]

\[ x = \frac{x_m - 0.25}{\tan(\alpha_{\text{ref}} - \frac{\alpha}{2}) \cdot \tan(\alpha - \frac{\alpha}{2})} + 0.25 \quad \text{and} \quad x_m = \frac{C_{m_0} - C_{m_{\text{ref}}}}{C_{i_{\text{ref}}} \cdot \cos \alpha_{\text{ref}} + C_{d_{\text{ref}}} \cdot \sin \alpha_{\text{ref}}} \]

The coefficient of the aerodynamical moment at zero lift $c_{m0}$ is derived from measurements or has to be defined. Fig. 8 shows the definition of the sign of the aerodynamical moments and the simulation of the „iced“ flat plate for high angles of attack.

![Fig. 8 Original iced profile and model of flat plate with „ice“ extension.](image-url)
5. ICE ACCRETION DURING OPERATION AND IDLING

On a pitch controlled turbine also leading edge ice accretion of up to 100 per cent could be observed during icing conditions. However, the turbine was not producing energy but was idling. At the same site and the same turbine only up to 40 per cent leading edge ice accretion have been documented during power production under icing conditions [2]. Fig. 9 illustrates the effect of icing under these two different operation conditions at a particular cross section. During power production the relatively high rotor speed causes centrifugal forces on the ice at the leading edge. Additionally, the Lift force $F_{ai}$ causes shear forces and bending moments between the ice and the blade, resulting in an early break off of the ice. The new ice growths leads to the well known saw tooth like leading edge ice formation along the radius. During idling the pitch angle is reduced and the rotor speed is very slow. The angle of attack at the sections is close to zero lift angle of attack and thus, no centrifugal loads nor relevant lift forces are acting on the ice growing at the leading edge resulting in a much bigger amount. A similar effect can be observed at slow rotating stall controlled turbines at low wind speeds and under icing conditions.

\[
\begin{align*}
\omega \cdot r & \quad \text{angular velocity of the rotor} \\
v & \quad \text{wind speed} \\
v' & \quad \text{reduced wind speed in the rotor area} \\
r & \quad \text{local radius} \\
\alpha & \quad \text{angle of attack} \\
v_{\text{eff}} & \quad \text{velocity to the airfoil} \\
F_{ai} & \quad \text{aerodynamic force acting on the leading edge ice}
\end{align*}
\]

Fig. 9 Bigger amount of leading edge ice accretion due to different operation conditions. Left side idling, right side power production of a pitch controlled turbine.
6. LOAD PREDICTION

Certifying wind turbines for cold and mountainous regions requires reliable procedures for the prediction of ice amount during standstill, idling and operation. As a result from the first JOULE - project *Icing on Wind Turbines* [1] a simplified load assumption for an ice mass distribution along the rotor radius has been worked out and was verified by further investigations during the WECO project [3]. Most of the observations at iced rotor blades during operation showed that the ice built-up is linear from the blade root to the tip with a maximum depth of ice accretion at the outer part representing also the highest ice mass. The maximum depth of ice amount at the tip is thereby depending on the blade’s chord length. This method described in [1] is recommended to predict the additional masses due to leading edge ice accretion without heating systems taken into account. The changed aerodynamic loads can be calculated by using the aerodynamic coefficients of the wind tunnel tests and the transformation described above. The blade loads in flapwise direction for a stall and a pitch controlled turbine are depicted in Fig. 10. In the partial power region the loads are decreased due to icing whereas beyond rated wind speed higher loads, even the highest loads can occur.

![Fig. 10 Blade root bending moments in flapwise direction at a pitch controlled turbine (left side) and for a stall controlled turbine (right side) for different ice accretion at the leading edge.](image)

Due to the increase of drag the turbine will not achieve rated power and thus, operate as a stall controlled turbine. For the stall controlled turbine the flapwise loads are diminished in the whole range of wind speed. However, it was assumed that all blades are iced similar and no aerodynamic unbalance occurs affecting the drive train, yaw mechanism, tower etc.. Also changed natural frequencies and higher excitation forces are not taken into account but may cause higher loads.
7. LOSS OF ANNUAL ENERGY PRODUCTION

The WECO ice atlas [6] giving the typical amount and duration of ice which can be expected at a specific site, the usually used wind speed prediction models and the aerodynamics of the iced airfoils in terms of power curves produce input data for the prediction of the annual energy output. Example calculations for a typical German inland site for two leading edge ice amounts, 5 per cent and 22 per cent at the blade tip were investigated for a duration of icing in the range of one day to three months [3] resulting in an energy loss of up to 20 per cent.

Fig. 11 Calculated power curve for a pitch controlled fictitious turbine with different types of ice accretion. Linear increase vs radius was assumed.

8. CONCLUSION

The aerodynamic coefficients $c_l$, $c_d$, and $c_m$, versus angle of attack were measured at a typical cross section of a wind turbine rotor blade with and without different types of ice at the leading edge in the wind tunnel of the University of Braunschweig. For higher angles of attack an extrapolation procedure is introduced. For the NACA4415 airfoil the data of the iced cross section can be directly taken as an input for the load and power calculation code without changing the blade’s geometry for other airfoils a transformation procedure is given. A recipe to estimate the aerodynamic and mass loads as well as the power curves and the annual energy output of an iced rotor is recommended and shown in Fig. 12.
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9. REFERENCES


