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The influence of leading edge roughness, rotor control and wind climate on the loss in energy production

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Abstract. This study investigates how losses in energy production from wind turbines are influenced by leading edge roughness, rotor control and wind climates using computations. The performance of a NACA63-418 airfoil with five different damage types was predicted using Computational Fluid Dynamics (CFD) with bumps at the leading edge and grooves into the leading edge. Also, one type corresponding to a repair of a leading edge with an “overbite” was investigated. These airfoil characteristics were used in rotor computations where three different wind climates and five different maximum tip speeds were investigated. The rotor computations reflected that the Annual Energy Production (AEP) increased significantly with the average wind speed on the site. They also reflected that the relative AEP losses due to leading edge damages reduced with increasing average wind speed on sites. For the low wind speed site the losses were between 1% and 4% depending on the extent and the type of the blade damage. For the high wind speed site the losses were between 0.5% and 3%. Furthermore, the bigger the extent of the damages were the bigger the losses were. Finally, it was shown that increasing the maximum tip speed increased AEP and decreased the losses.

1. Introduction

It is known from several studies that Leading Edge Roughness (LER) or Leading Edge Erosion (LEE) affect the Annual Energy Production (AEP) of wind turbines. Numbers are computed to predict the losses in production and losses up to 25% due to heavy erosion with a corresponding severe increase in drag have been reported, see e.g. Sareen et al.[1]. However, how the surface damages at the leading edge are influencing the aerodynamic performance of airfoils and rotors are still discussed, see e.g. [2, 3, 4, 5, 6, 7, 8, 9]. An obvious approach to the issues of erosion is to prevent the surface damages to appear. With respect to these two ways to prevent this are at the moment analyzed. One way is to use advanced leading-edge protection materials, which need to be developed further. This material is often glued onto the surface of the blade leading edge and results in small backward facing steps at both the pressure side and suction side. Another way is to reduce the tip speed in certain climatic events e.g. in heavy rain. Here, Bech et al. [10] has carried out an investigation of the influence of rain and tip speed and its effect on erosion and the corresponding impact on AEP.

Based on the many investigations of LER and LEE it is clear that the performance due to surface damages at the leading edge is a complex matter. Therefore, this study will zoom out on the overall conditions for the rotor in terms of aerodynamic performance. In this paper the aerodynamic rotor performance will be analyzed computationally using airfoil characteristics affected by different surface imperfections using 2D Computational Fluid Dynamics (CFD), but also predict the aerodynamic rotor performance using different rotor control settings and wind climates in a Blade Element Momentum (BEM) code. In this way a broader overview and understanding of the performance can be provided.
The present work is based on a study using Computational Fluid Dynamics (CFD) on how surface imperfections affect the aerodynamic performance of 2D airfoils. In this study the performance was investigated at four different Reynolds numbers: 3, 5, 7 and 10 million. In the current work only data with a Reynolds number of 5 million was used for simplicity and because this Reynolds number corresponds to wind turbines up to around 3MW. However, the aerodynamic effect of LER depends on the Reynolds number. More about this is described by Bak et al. [11]. The different types of degraded airfoil characteristics from the CFD study are used for rotor computations with different control setting and wind climates. Thus, even though surface imperfections show a degraded performance for a single airfoil, the influence on the AEP depends on several other conditions such as the Weibull distribution and the maximum tip speed. Thus, the objectives of this study is to map the parameters influencing the loss in AEP in connection to LER. More specifically results from three different wind climates will be shown together with changes in maximum tip speed and the airfoil characteristics on the outer part of the rotor, i.e. the outer 10%, 20% and 30% of the radius.

2. Methods

Basically two methods are used. One method that predict the airfoil characteristics and one method that predicts the rotor performance. These two methods will be described in the following.

2.1. Predicting the airfoil characteristics

Computational Fluid Dynamics (CFD) using EllipSys [12,13,14] was used to analyze the effect of surface imperfections on the aerodynamic performance in 2D on a NACA 633-418 airfoil with a relative thickness of 18% corresponding to an airfoil used on the outer part of a rotor. The results from this 2D CFD analysis is a number of polars that compared to a clean and smooth surface shows a degraded performance. The basis of the polars are a big parameter study investigating the influence of surface damages on the aerodynamic performance. Many of the damages were modelled directly into the mesh so that the effect of bumps and grooves could be predicted. In the present study only eight of these polars are used:

- **Clean**: This is the airfoil with the best performance that is possible, i.e. no assumed damages and assuming free transition from laminar to turbulent flow
- **Turb**: This is with the same assumptions as above, however assuming fully turbulent flow with no laminar flow
- **Mixed**: This is a mix of the two above computations. 70% Clean and 30% Turb. This is a mix that some blade designers use to estimate the “true” aerodynamic performance because the Clean performance according to the experience show too low drag and too high maximum lift in relation to the performance of rotors performing under realistic conditions.
- **Bump**, \( h/c = 0.001 \) to \( x/c = 0.03 \): This is an otherwise clean airfoil with a step out of the surface at the leading edge with a height \( (h) \) relative to the chord \( (c) \) of \( h/c = 0.001 \) from \( x/c = 0.03 \) at the pressure side to \( x/c = 0.03 \) at the suction side. This can be interpreted as a leading edge protection
- **Bump**, \( h/c = 0.001 \) to \( x/c = 0.08 \): This is an airfoil as described above, but with the step out of the surface from \( x/c = 0.08 \) at the pressure side to \( x/c = 0.08 \) at the suction side
- **Erosion**, \( d/c = 0.001 \) to \( x/c = 0.01 \): This is an otherwise clean airfoil with a groove into the surface at the leading edge with a depth \( (d) \) relative to the chord \( (c) \) of \( d/c = 0.001 \) from \( x/c = 0.01 \) at the pressure side to \( x/c = 0.01 \) at the suction side
- **Erosion**, \( d/c = 0.002 \) to \( x/c = 0.01 \): This is an airfoil as described above, but with a groove into the surface of \( d/c = 0.002 \)
- **Overhang**: An overhang (or an “overbite”) at the leading edge between the suction side of the airfoil and the pressure side of the airfoil can exist. This will however often be removed or smoothened. This polar shows how an overhang of \( h/c = 0.0025 \) that is filled up will affect the aerodynamics.

The different polars are shown in Figure 1 with the lift coefficient, \( c_l \), as a function of the drag coefficient, \( c_d \), to the left and the lift coefficient, \( c_l \), as a function of the angle of attack, \( AOA \), to the right.
A comment to these polars is that there is no prediction of e.g. a groove with a sandpaper-like surface in the bottom of this groove. In wind tunnel tests it is seen that $c_d$ in this case increases and $c_l$ decreases further [15]. Therefore, in the evaluation of the predicted data $c_d$ could be even higher and $c_l$ could be lower in real situations of erosion.

2.2. Predicting the rotor performance

The data from the 2D CFD computations was used together with HAWTOPT [16] which is a Blade Element Momentum (BEM) code, where the rotor speed and pitch can be controlled and carries out steady state computations. This code can also compute AEP. The basis for the wind turbine used in this computational study is a Vestas V52. However, since the rotor control and the airfoil characteristics are changed, this model is not matching the performance of a Vestas V52. In fact, it is not very important which wind turbine and which size is used. More important is the specific rated power (the rated power divided with the swept area of the rotor) which in this case is about 400W/m². To make this study more generic, all results are normalized. In this way the size is only seen via the Reynolds number in the CFD computations.

The way that the airfoil characteristics are introduced into the BEM code is by exchanging the existing airfoil characteristics with the predicted airfoil characteristics for the outer part of the blade. The HAWTOPT code has the airfoil characteristics defined the same way as in the FLEX code [17].

Using the different data for the NACA633-418 airfoil it is ensured that the data is used from radii 70%, 80% and 90%, respectively, and outwards. One file with airfoil characteristics per configuration was generated. When computing the power curves it is assumed that the optimal tip speed ratio (TSR) is constant until maximum tip speed is reached. When maximum tip speed is reached the rotor is operated with constant rotational speed and constant pitch until rated power is obtained. When rated power is reached the rotor starts to pitch. Figure 2 shows power curves using “Clean” and “Erosion, $d/c=0.002$ to $x/c=0.01$” polars corresponding to those shown in Figure 1. In the shown power curves the polars are used from 70% radius to the tip. It is clear that the maximum tip speed is affecting the power curves. It is also clear that there is a difference in power curves when assuming clean and contaminated airfoils.
The power curves are predicted with the assumption that the aerodynamics and the operation is steady state and the structure is infinitely stiff even though the wind turbine operation in reality experiences unsteady inflow and a flexible tower and blades. The aerodynamic rotor characteristics are shown in Figure 3, where the power coefficient, $CP$, as a function of the tip speed ratio, $TSR$ or $\lambda$, for the different degraded airfoil characteristics are seen. $TSR$ is kept constant in the BEM computations in the variable speed range of the power curve and for all degraded cases the rotor operates in a narrow range of $TSR$’s between $TSR=8.63$ and 8.99 as seen in the legend. However, a real controller will probably have challenges in tracking the optimal $TSR$ so there can be changes over the variable speed range, and it is likely that most commercial turbine controllers cannot obtain a constant $TSR$, see investigations of extremum-seeking controllers, e.g. [18, 19, 20]. Thus, with the assumption of steady state and an infinitely stiff turbine, the predictions in this work are simplified. However, the changes in the optimal $TSR$ due to the leading edge conditions are small and because $CP$ is only varying slightly as a function of $TSR$ around maximum $CP$ it is believed that the results show the correct trends even though the controller cannot keep constant $TSR$.

Figure 3. Power coefficients, $CP$, as a function of the Tip Speed Ratio, $TSR$ or $\lambda$, for different surface conditions at the leading edge. The dotted black lines show the range where the rotor operates in the variable speed range of the power curve.
When computing the AEP, a Weibull distribution is used with the shape parameter $k=2$ and the scale parameter $C$ set to 6.77m/s, 9.03m/s and 11.28m/s, respectively. These $C$ parameters are found from $C=2V_{ave}^2/\pi^{0.5}$ from the IEC 61400-1 standard (3rd ed) assuming that the average wind speed is $V_{ave}$ 6m/s, 8m/s and 10m/s, respectively.

3. Results

Computations are carried out varying a number of parameters:
- The wind climate with three different Weibull distributions:
  - $C=6.77$m/s
  - $C=9.03$m/s
  - $C=11.28$m/s
- The maximum tip speeds with:
  - $V_{tip}=70$m/s
  - $V_{tip}=75$m/s
  - $V_{tip}=80$m/s
  - $V_{tip}=85$m/s
  - $V_{tip}=90$m/s
- The airfoil characteristics with eight different sets as described in section 2.1.
- The part of the blade that is covered with damages:
  - Radius 70% to 100%
  - Radius 80% to 100%
  - Radius 90% to 100%

Combining this gives a total of 300 cases. In Figure 4 the specific AEP (the AEP per square meter of swept area) is seen for three different wind climates. From left to right are seen wind climates with $C=6.77$m/s, $C=9.03$m/s and $C=11.28$m/s, respectively. It is clear that AEP is increasing for increasing $C$ parameter, but it is also clear that AEP is increasing for increasing maximum tip speed. 3.504 MWh/m² corresponds to 100% capacity factor. Thus, the maximum capacity factor in the three wind climates are 24%, 42% and 55%, respectively. When analyzing the performance of the different damage types it is worth noticing that “Clean” corresponds to a very clean surface. Also, “Overhang” seems not to affect the performance a lot as long as the surface is smooth with no edges. “Mixed” shows that a realistic performance is slightly lower than “Clean”, but still shows very good performance. “Bump, $h/c=0.001$ to $x/c=0.08$” shows some losses and corresponds closely to airfoil characteristics assuming fully turbulent flow “Turb”. Thus, it seems that the backward facing step at $x/c=0.08$ (8% from the leading edge on both suction side and pressure side) ensures transition from laminar to turbulent flow, but it does not induce much form drag. “Erosion, $d/c=0.001$ to $x/c=0.01$” shows almost the same losses as “Turb”, but it is somewhat worse at lower maximum tip speeds probably due to the lower maximum $c_t$. The two damage types that show the biggest losses are “Bump, $h/c=0.001$ to $x/c=0.03$” and “Erosion, $d/c=0.002$ to $x/c=0.01$”. It is believed that “Erosion, $d/c=0.002$ to $x/c=0.01$” in real life will show even bigger losses because the sandpaper like roughness in the bottom of the groove is not modelled in these CFD computations. However, it is interesting that “Bump, $h/c=0.001$ to $x/c=0.03$” that corresponds to e.g. a tape or a Leading Edge Protection (LEP) device shows relative big aerodynamic losses. As shown in the plots the losses from the “Bump” case becomes smaller if the backward facing step is moved downstream from $x/c=0.03$ to e.g. $x/c=0.08$. 
Further to this it is seen that the different types of damages on the airfoil result in different decrease of AEP. An understanding of the impact of these damages is easier if it is compared to the clean case. This is done in Figure 5, where the loss in AEP compared to AEP assuming clean data is shown for the three different wind climates (each row) and for different parts of the blade covered with damages (each column). According to this figure the loss in AEP is below 0.5% if the damages are found on the outer 10% of the blade in a wind climate corresponding to $C=11.28\text{m/s}$ (lower right plot). This loss increases to around 1% if the average wind speed is lower corresponding to $C=6.77\text{m/s}$ (upper right plot). Opposite, if the damages are covering the outer 30% of the blade and there is a low average wind speed corresponding to $C=6.77\text{m/s}$, then the losses can be 3% and even higher (upper left plot). In a wind climate with $C=11.28\text{m/s}$ with the damages covering the outer 30% of the blade the losses can according to the computations be between 1% and 3% (lower left plot). When studying the plots in Figure 5 further, the observations made for Figure 4 are the same. Thus, “Bump, $h/c=0.001$ to $x/c=0.03$” (the surface corresponding to e.g. an LEP tape) and “Erosion, $d/c=0.002$ to $x/c=0.01$” (a surface with a groove with depth of 2 per mille of the chord length) show the biggest losses.
Figure 5. Loss in AEP compared to AEP assuming clean airfoils. Left column: Assumption of damages from 70% to 100% radius, Mid column: Assumption of damages from 80% to 100% radius, Right column: Assumption of damages from 90% to 100% radius. Top row: $C=6.77$ m/s in Weibull distribution, Mid row: $C=9.03$ m/s in Weibull distribution, Low row: $C=11.28$ m/s in Weibull distribution.
Figure 6 shows how AEP increases with maximum tip speed, where the changes in AEP relative to the AEP predicted for a maximum tip speed of 70m/s are shown. In the plot it is seen that the gain in AEP as a function of the maximum tip speed decreases with increasing average wind speed. Thus, in the left plot (C=6.77m/s) an increase between 3% and 4% is seen, whereas in the right plot (C=11.28m/s) an increase between 2% and 3.5% is seen. It is also seen that the increase at lower tip speeds (70m/s to 80m/s) is somewhat bigger than at higher tip speeds (80m/s to 90m/s). Especially for the two damage types “Erosion, d/c=0.001 to x/c=0.01” and “Erosion, d/c=0.002 to x/c=0.01” a significant increase in AEP is seen for increasing maximum tip speed. This is likely because of the significant loss in maximum lift for these damage types. Thus, the higher the maximum tip speed is the less the need for a reserve between the design lift and the maximum lift is. Therefore, the study indicates that the reduced maximum lift in case of erosion becomes less critical the higher the maximum tip speed is.

![Figure 6. Increase in AEP compared to AEP at a tip speed of 70m/s and with damages from 70% radius to 100% radius. Results from three different C parameters in the Weibull distribution are shown. Left plot: C=6.77m/s, Mid plot: C=9.03m/s, Right plot: C=11.28m/s.](image)

4. Conclusion
The performance of a NACA631418 airfoil with five different damage types was predicted using Computational Fluid Dynamics (CFD). The five types included two types with a step out of the surface corresponding to e.g. a tape on the leading edge, two types with grooves of different depths into the leading edge corresponding to an erosion case and one type corresponding to a repair of a leading edge with an “overbite”. Two more predictions using CFD were made: One assuming free transition from laminar to turbulent flow and one assuming fully turbulent flow. Finally there was one more set that corresponded to a mix between the free transition prediction and the fully turbulent prediction. Such a
mix is often used in the aerodynamic rotor design process and is intended to simulate a realistic performance of a rotor without too many damages.

The above airfoil characteristics were used in rotor computations where three different wind climates and five different maximum tip speeds were investigated to study the Annual Energy Production (AEP). The impact of Leading Edge Roughness (LER) on loads were not investigated. It should be emphasized that the Blade Element Momentum (BEM) code that was used was a steady state code without turbulent flow and with simplified control of pitch and rotor speed compared to a wind turbine. Even though the computations were simplified, it is believed that the most important trends in the AEP losses are predicted.

The rotor computations reflected as expected that AEP increased significantly with the average wind speed on the site. They also reflected that the AEP losses due to leading edge damages reduced with increasing average wind speed on sites. For the low wind speed site (C=6.77m/s) the losses were between 1% and 4% depending on the extent of the blade damage and for the high wind speed site (C=11.28m/s) the losses were between 0.5% and 3%. The bigger the extent of blade damages were the bigger the losses were. Furthermore, it was shown that increasing the maximum tip speed increased the AEP. The increase for lower tip speeds (70m/s to 80m/s) is bigger than for higher tip speeds (80m/s to 90m/s).

For the five damage types it was seen that a repair of an overhang between the suction side and the pressure side (an “overbite”) did not affect the AEP much. It seems that as long as the airfoil has a smooth surface the performance is almost unaffected. Also, the damage types with a groove into the surface (corresponding to erosion but with no sandpaper-like surface at the bottom of the groove) showed the biggest losses for lower maximum tip speeds. However, at higher maximum tip speeds the groove with the smaller depth (d/c=0.001) showed limited impact. This impact was at the level of the “bump” type (corresponding to leading edge protection) with height h/c=0.001 extending to x/c=0.08. An interesting result was that the “bump” type that extended to only x/c=0.03 showed relative big losses comparable to a groove with a depth of d/c=0.002. Finally, the investigations showed that the assumptions of fully turbulent flow that is often used in predictions of aerodynamic performance as the case of LER, was not sufficient to simulate the aerodynamic degradation that was seen with grooves and bumps in the surface.

This study showed that with a moderate damage of the leading edge the losses for a wind turbine with a specific power of around 400W/m² can vary between 0.5% and 4% depending on the parameters from the wind climate, the extent of the blade damage and the maximum tip speed. Thus, when evaluating the effect of LER it is important to consider these parameters in the evaluation.

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