Technical University of Denmark

DTU

What is the critical height of leading edge roughness for aerodynamics?

Bak, Christian; Gaunaa, Mac; Olsen, Anders Smærup; Kruse, Emil K.

Link back to DTU Orbit

DTU Library
Technical Information Center of Denmark

What is the critical height of leading edge roughness for aerodynamics?

Christian Bak[1], Mac Gaunaa[1], Anders S. Olsen[1], Emil K. Kruse[2]

[1]Tech. Uni. of Denmark, Dept. Wind Energy, Frederiksborgvej 399, 4000 Roskilde, DK
[2]Power Curve, Stationsmestervej, 9200 Aalborg SV, DK

chba@dtu.dk

Abstract. In this paper the critical leading edge roughness height is analyzed in two cases: 1) leading edge roughness influencing the lift-drag ratio and 2) leading edge roughness influencing the maximum lift. The analysis was based on wind tunnel measurements on the airfoils NACA0015, Risoe-B1-18 and Risoe-C2-18 and at three different Reynolds numbers with two different leading edge roughness tape heights. Firstly, an analysis of the momentum thickness as function of Reynolds number was carried out based on the boundary layer theory by Thwaites. Secondly, the wind tunnel measurements combined with panel code predictions of the boundary layer momentum thickness created the basis for determining the impact of roughness on the aerodynamic performance. The critical heights were related to the Reynolds numbers and thereby the size of the wind turbines.

1. Introduction

Irregular and non-smooth surfaces at the leading edge of wind turbine blades can cause a loss of energy production. For many years there has been a focus on leading edge roughness (LER) from not only the wind turbine industry, but also from e.g. the aviation industry. This is because it is known that LER can cause reduced aerodynamic performance, e.g. [1,2,3]. Recently there has been an increasing focus on this issue because the volume of wind turbines is growing and because erosion of blade leading edges has been more and more pronounced, e.g. [4,5]. Thus, Sareen et al. [4] concludes that the loss in annual energy production could be as high as 25% if severe roughness appears at the leading of a blade. This is the reason that leading edge roughness is an important issue.

Since the start of the 1980s there has been a continuous upscaling of wind turbines. A result of the upscaling is that the chord length is increasing proportionally with the general upscaling, which again results in an increase of the Reynolds number because the tip speed is almost constant. An increase in Reynolds number will lead to thinner boundary layers relative to the airfoil chord. The question is therefore: What is the critical height of LER below which aerodynamic performance is not affected?

This paper will through analytical and numerical considerations and analysis of wind tunnel tests investigate the sensitivity to different LER heights at different Reynolds numbers and study the critical size below which the aerodynamic performance in terms of lift-drag ratio and maximum lift remain unaffected to avoid losses in the aerodynamic performance and thereby in the annual energy production. Since airfoils and blades obtain their maximum performance if the first part of the boundary layer is laminar (with a transition to turbulence further downstream) we assume in this investigation laminar boundary layers starting from the leading edge. This implies hydraulically smooth surfaces and low turbulence intensity below 0.1%.

2. Methods

This section describes the different methods used to analyze the effect of LER on the aerodynamic performance for different sizes of wind turbines.

2.1. Analytical investigation using Thwaites method

Assuming attached flow around an airfoil and assuming that the boundary layer (BL) is laminar, Thwaites method (see textbooks such as for instance White [6]) can be used to calculate the momentum thickness (MT) of the boundary layer along the airfoil surface:

$$\theta^2(\hat{x}) = \frac{c}{U_\infty} 0.45\nu \frac{\int_0^{\hat{x}} f^5(\hat{\hat{x}}) d\hat{\hat{x}}}{f^6(\hat{x})} \tag{1}$$

Here θ is the MT, ν is the dynamic viscosity, U_∞ is the far field inflow velocity, $\hat{x}$ and $\hat{\hat{x}}$ is the coordinate parallel to the flow direction normalized with the airfoil chord length (so specifying the non-dimensional location along the airfoil surface) and c is the chord length. Furthermore, the ratio of the velocity just outside the BL to the far field velocity is denoted $f(\hat{x}) = U(\hat{x})/U_\infty$ or $f(\hat{\hat{x}}) = U(\hat{\hat{x}})/U_\infty$. Since the scope of the present investigation is an orders of magnitude analysis to investigate under which conditions leading edge roughness influences the airfoil performance, we therefore consider cases at constant angle of attack where $f(\hat{x})$ has the same shape along the airfoil surface. Under this condition it is seen that the last fraction in Eq. (1) is simply a function of the relative position along the airfoil, $\hat{x}$. Thus, we can write $F(\hat{x}) = \frac{\int_0^{\hat{x}} f^5(\hat{\hat{x}}) d\hat{\hat{x}}}{f^6(\hat{x})}$. For these cases Eq. (1) can therefore be written in the more convenient form

$$\theta^2(\hat{x}) = \frac{c}{U_\infty} 0.45\nu F(\hat{x}) \tag{2}$$

If it is assumed that the first-order impact of surface roughness on the boundary layer is determined by the ratio between the size of the roughness, Δ, and the momentum thickness, θ, the sensible roughness-size parameter will be $RRH = \frac{\Delta}{\theta}$, where RRH is the relative roughness height. Insertion of the result from Eq. (2) yields:

$$RRH = \frac{(\Delta/c)\sqrt{Re}}{\sqrt{0.45F(\hat{x})}} \quad <=> \quad \frac{\Delta}{c} = RRH\sqrt{0.45F(\hat{x})}\sqrt{\frac{1}{Re}} \tag{3}$$

Here $Re = \frac{U_\infty c}{\nu}$ is the Reynolds number for the airfoil flow and $\sqrt{0.45F(\hat{x})}$ is a fixed function for a given airfoil and angle of attack. Therefore the important result from this analysis is that if we wish to maintain the RRH as a constant[1] then $\frac{\Delta}{c} \sim \sqrt{\frac{1}{Re}}$. Since the tip speed is almost the same for all modern wind turbine rotors (between 80m/s and 100m/s) then $Re \sim c$ for a given relative location along the blade span. This means that the relative roughness height is $\frac{\Delta}{c} \sim \sqrt{\frac{1}{c}}$ or that we can allow that the absolute roughness height can vary as

---

[1] And thereby the effect of the surface roughness.

$$\Delta \sim \sqrt{c} \qquad\qquad\qquad\qquad\qquad (4)$$

Thus, a given size of roughness (a bug or a salt crystal) at a given ratio along the blade will affect small wind turbine rotors more than big wind turbine rotors, but a direct upscaling of roughness with the chord length, c, will affect big wind turbine rotors more than small wind turbine rotors.

2.2. The panel code XFOIL

The XFOIL code [7] is used to predict the BL and MT of the three airfoils. For a given *AOA* and *Re*, the code provides *cp*-distributions, c_l, and c_d and in addition, numerous boundary layer parameters. In combination with the analysis of the wind tunnel tests, the MT for certain *AOA* is calculated to be able to compare with the leading edge roughness tapes mounted on the airfoil. In the calculations 120 panels are used and $n=7$ in the e^n transition model corresponding to the turbulence intensity in the wind tunnel tests. Since the drag is determined from the wake momentum thickness far downstream and drag predicted by XFOIL in general is in good agreement with wind tunnel measurements the prediction of MT is believed to be well predicted.

2.3. Wind tunnel tests

Three airfoils were tested in the LM Wind Power LSWT wind tunnel in Lunderskov, Denmark: *NACA0015 [8], Risø-B1-18 [9] and Risø-C2-18 [10]*. The Reynolds numbers were at $Re = 1.6*10^6$, $3.0*10^6$ and $6.0*10^6$. Steady state polar measurements were conducted with several different configurations of the airfoils, e.g. clean surface with no LER on the airfoil and LER simulated by two different types of tapes: 1) the bump tape (bump2) with a height of 0.1mm and 2) the zigzag tape (ZZ2) with a height of 0.4mm. Both tapes are mounted at $x/c = 2\%$ on the suction side. The airfoils had a chord of 0.900 m. The bump tape has the normalized height $h/c=110*10^{-6}$ and the zigzag tape has the normalized height $h/c=440*10^{-6}$.

3. Results

To understand the BL's of the airfoils, computations using XFOIL were carried out to predict the MT. In Figure 1 the MT at $x/c=2\%$ normalized with the chord length are shown for the three airfoils and for three *Re*'s. It is seen that the MT that is normalised with the chord is almost the same for all three airfoils for each c_l and *Re*. The MT decrease as *Re* and *AOA* (and thereby c_l) increase. For constant *Re* there is a reduction in MT of between 20% and 30% from the lowest lift value to maximum lift. For constant *AOA* there is a reduction in MT of close to 30% when doubling *Re*.

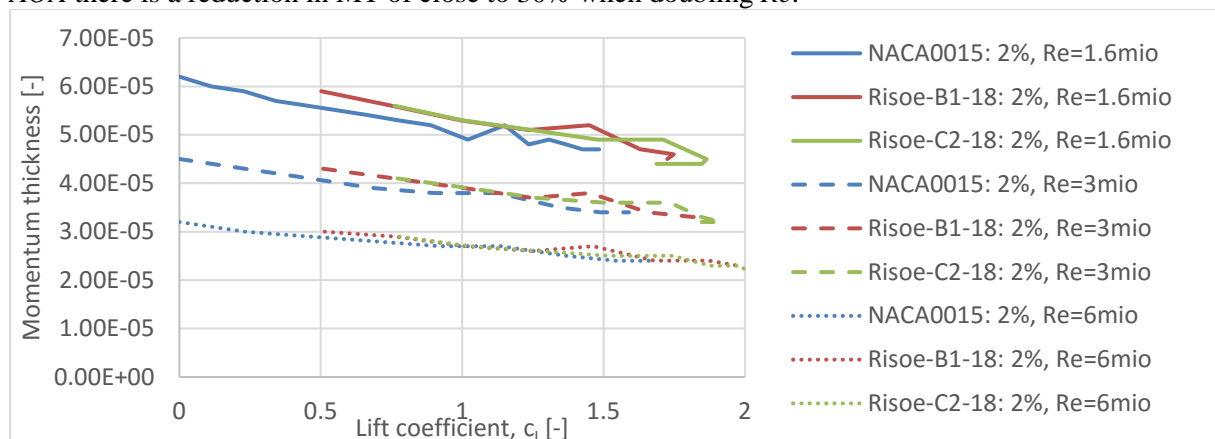*Figure 1 Momentum thickness (MT) at x/c=2% as a function of lift coefficient, (c_l) predicted using XFOIL.*

By analyzing wind tunnel tests it was investigated which tape heights that are critical to the aerodynamic performance. In the following results from three different analysis are shown. Firstly, the model described by Eq. (4) is investigated and validated. Secondly, the increase in drag due to the tape is

investigated to find the critical roughness height. A possible drag increase results in a power decrease for wind speeds below rated power, i.e. in the part of the power curve where maximum power is desired. Thirdly, the reduction of maximum lift due to the tape is also investigated to find the critical roughness height. A possible decrease in maximum lift results in a power decrease for wind speeds just below rated power, i.e. the shoulder of the power curve where a significant amount of power can be lost.

3.1. Validating the analytical model

Computing the *MT* using XFOIL at *AOA*=8° or c_l=1.45 makes an evaluation of the critical height of the tapes possible. At this *AOA* the position of the transition point on the suction side is according to XFOIL *x/c*=13.6% at *Re*=1.6*10^6, *x/c*=6.5% at *Re*=3*10^6 and *x/c*=4.4% at *Re*=6*10^6. Figure 2 shows the MT close to the leading edge for three different *Re*'s, where MT is normalised with the chord. Also, the tape heights are shown. The black line shows the height of the bump tape and the grey line shows the height of the zigzag tape. It is seen that the scaling of the laminar BL at *Re*=1.6*10^6 to *Re*=3.0*10^6 and to 6.0*10^6 based on Thwaites method (Eq. 3) fits well for the part of the BL that is laminar, i.e. for the first 4.4% to 6.5% depending on *Re*. With this validation it is confirmed that the laminar part of the BL can be scaled with $(1/Re)^{0.5}$ if the chord is kept constant. If *Re* is increased by increasing the chord, the BL is scaled by $Re^{0.5}$. It means that the BL can be scaled with $c^{0.5}$ when assuming that the tip speed is constant for different sizes of wind turbines.
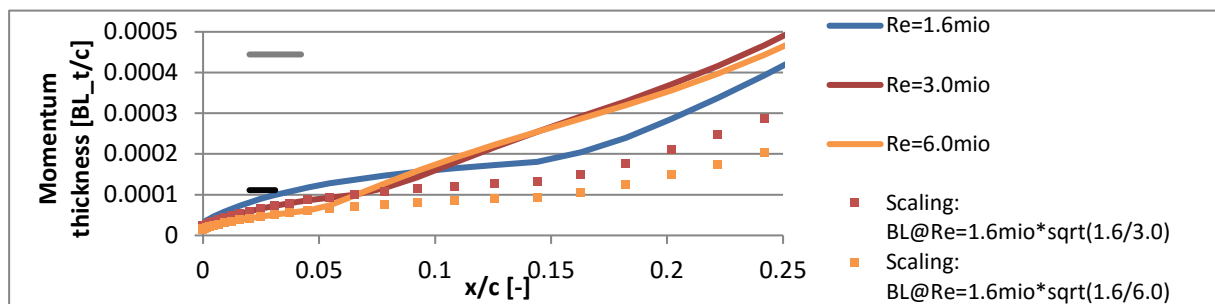

Figure 2 MT vs chord position for three different Re's using XFOIL, n=7 in the e^n transition model.

3.2. Increase in drag

In Figure 3 the lift coefficient as a function of the drag coefficient as measured in the wind tunnel is shown for three airfoils and at three *Re*. From the plots in Figure 3 it is seen that the blue curves show the clean cases and the red curves show those where the bump tape is attached. It is also seen that the drag coefficient for the cases with bump tape at a certain lift coefficient increases more than the clean cases. The lift coefficient and the corresponding *AOA* where the drag coefficient starts to increase is noted as approximate values. This is shown below in Table 1 together with the corresponding *MT* predicted with XFOIL at the corresponding *Re* and *AOA* at the location of the tape. Also, the height of the bump tape (called *Tape Height* or in short *TH*) is shown relative to *MT, TH/MT*. Based on the values shown in Table 1, *TH/MT* is shown as a function of *Re* in Figure 4. From the relation between *TH/MT* and *Re* we can see that it seems that we can allow a higher *TH* at high *Re* than at low *Re* compared to *MT*, and it seems that it roughly is proportional to $Re^{0.3}$ (or $c^{0.3}$ if the tip speed is constant). With *TH/MT*~$c^{0.3}$ and with *MT*~$c^{0.5}$ as shown earlier in this paper the results indicate that *TH*~$c^{0.8}$. Since *TH* is proportional to the roughness height *Δ* we can also write *Δ*~$c^{0.8}$.

Since the critical roughness height is observed at lower *AOA* for increasing *Re*, the observations are made for different pressure gradients. At high *AOA* corresponding to low *Re* the pressure gradients are adverse because a suction peak is upstream of *x/c*=2%. In this case the BL will be weaker downstream of the roughness. At lower *AOA* corresponding to high *Re* the pressure gradients are favourable and in this case the BL will be stabilised downstream of the roughness. Since the influence of the roughness is seen at high *AOA* at low *Re* and low *AOA* at high *Re* the conditions are not completely similar at the different *Re*'s. Therefore, the relation *Δ*~$c^{0.8}$ is uncertain and the exponent is likely to be below 0.8.
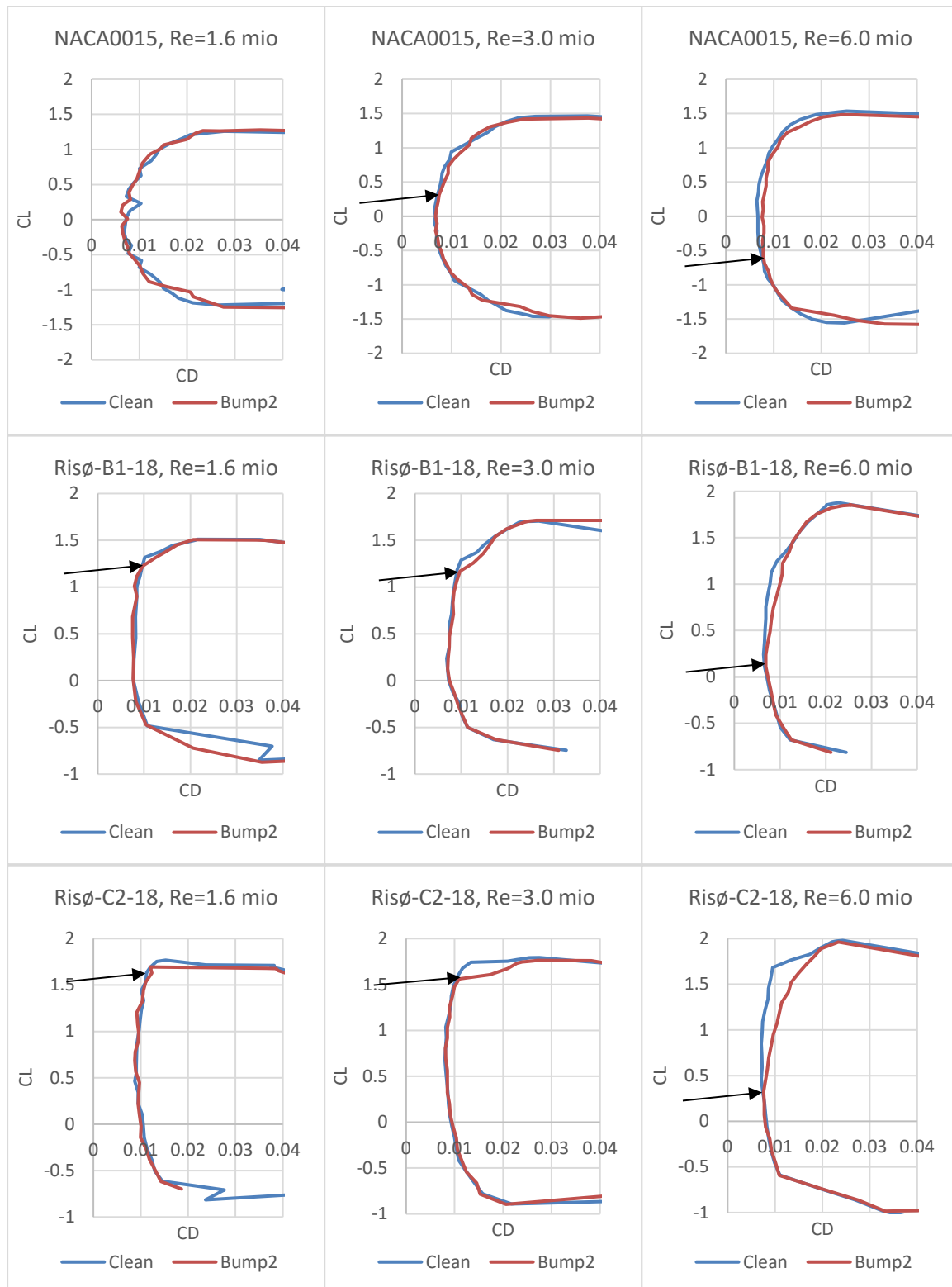
Figure 3 Lift coefficient c_l as a function of drag coefficient c_d for three different airfoils: 1) NACA0015 (top), 2) Risø-B1-18 (mid) and 3) Risø-C2-18 (bottom) and for three different Re: a) Re=1.6*10^6 (left), b) Re=3.0*10^6 (mid) and c) Re=6*10^6 (right). The arrows indicate at which c_l the lift-drag ratio decreases caused by the LER.

Table 1 Corresponding values of AOA and c_l from wind tunnel tests and MT from XFOIL for three airfoils and at three Re's, where the drag coefficient increases due to the existence of a bump tape compared to the clean case.

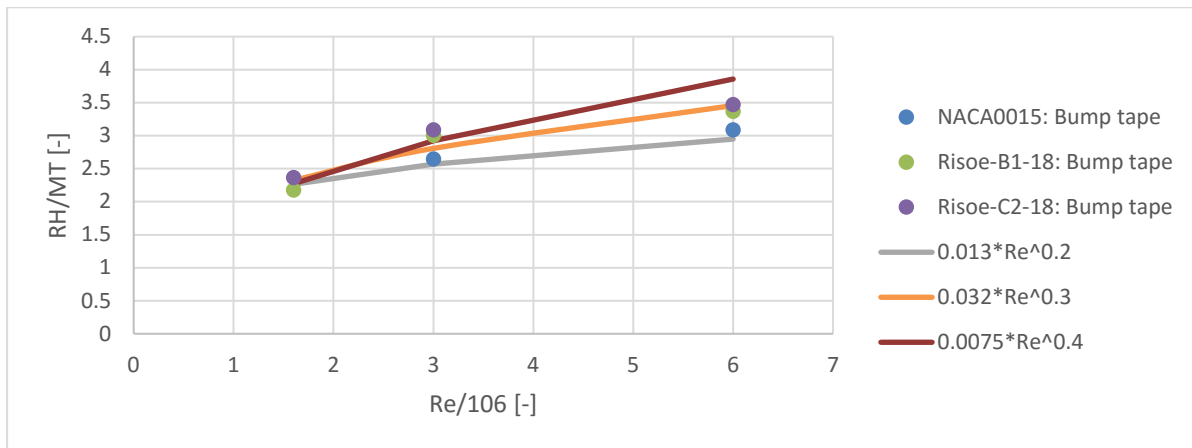|	$Re/10^6$	~AOA	~c_l	MT	TH/MT
NACA0015	3	3	0.32	$42*10^{-6}$	2.65
	6	-5	-0.6	$36*10^{-6}$	3.09
Risø-B1-18	1.6	7	1.23	$51*10^{-6}$	2.18
	3	6	1.16	$37*10^{-6}$	3.00
	6	-3	0.1	$33*10^{-6}$	3.37
Risø-C2-18	1.6	9	1.6	$47*10^{-6}$	2.36
	3	8	1.6	$36*10^{-6}$	3.09
	6	-3	0.3	$32*10^{-6}$	3.47

Figure 4 The bump tape height (TH) relative to the momentum thickness (MT) where the drag starts to increase as a function of Reynolds number.

With a direct scaling of the *DTU-10MW-RWT* wind turbine [11] and assuming that tip speed, pitch etc. are constant, the bump height (i.e. the height of a roughness element) at *x/c*=2% at rotor radius *r/R*=80.7% can within orders of magnitude be predicted for different rotor sizes. If we assume that a 0.1mm bump tape is the critical height for not influencing the aerodynamic performance at $Re=1.6*10^6$ for an airfoil with chord 0.900 m, then the corresponding bump height is 0.04 mm if the rotor diameter is 23 m because the chord for this size of rotor is 0.376m at *r/R*=80.7% and the local speed is 64.4m/s. Assuming that the roughness height relates to the chord as shown by the analytical investigation ($\Delta \sim c^{0.5}$), the critical bump height is e.g. 0.08 mm for an 80 m rotor corresponding to a 2MW wind turbine. If the roughness height relates to the chord as indicated by the measurements ($\Delta \sim c^{0.8}$), the critical bump height is e.g. 0.11 mm for an 80 m rotor. Because this investigation is based on rather few measurements there is some uncertainty related to the trends. However, the aerodynamic performance will be influenced by a minimum leading edge roughness height that is following the $c^{0.5}$ trend (red curve in Figure 5), and a maximum leading edge roughness height will follow the $c^{0.8}$ trend (blue curve in Figure 5). Thus, the leading edge roughness height will be found in between the $c^{0.5}$ trend curve and the $c^{0.8}$ trend curve. It should be noted that for rotor diameters above 100m, the chord length are so big that *Re* is greater than $6*10^6$. Therefore, since this study are investigating airfoils measured at *Re*'s between $1.6*10^6$ and $6*10^6$ the observed relations are extrapolated from the wind tunnel tests if the rotor sizes exceed 100 m diameter.
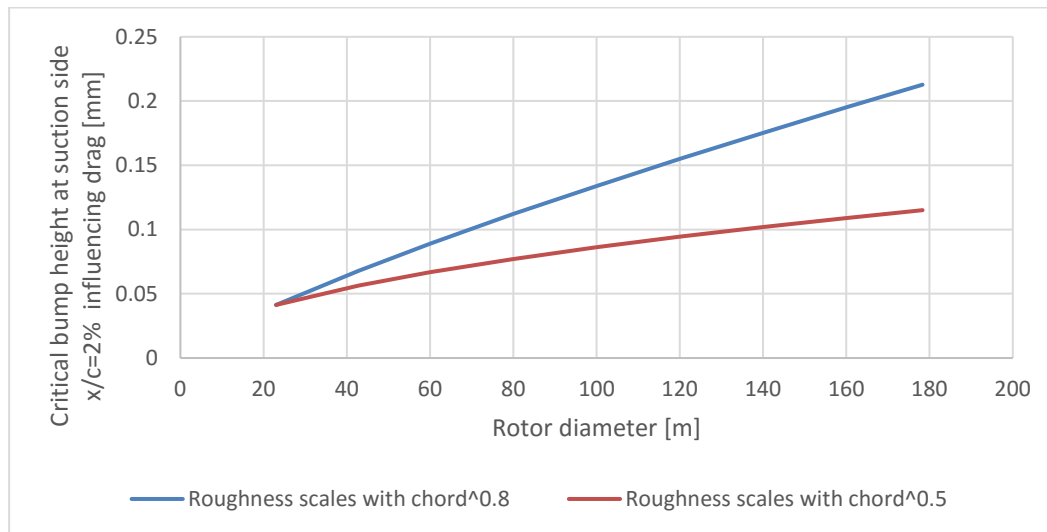
Figure 5 The critical bump height at the suction side x/c=2% at r/R=80.7% under which the drag remains unaffected.

3.3. Decrease in maximum lift

In Figure 6 lift curves measured in the wind tunnel are seen for the three airfoils NACA0015, Risø-B1-18 and Risø-C2-18 at $Re=3*10^6$.
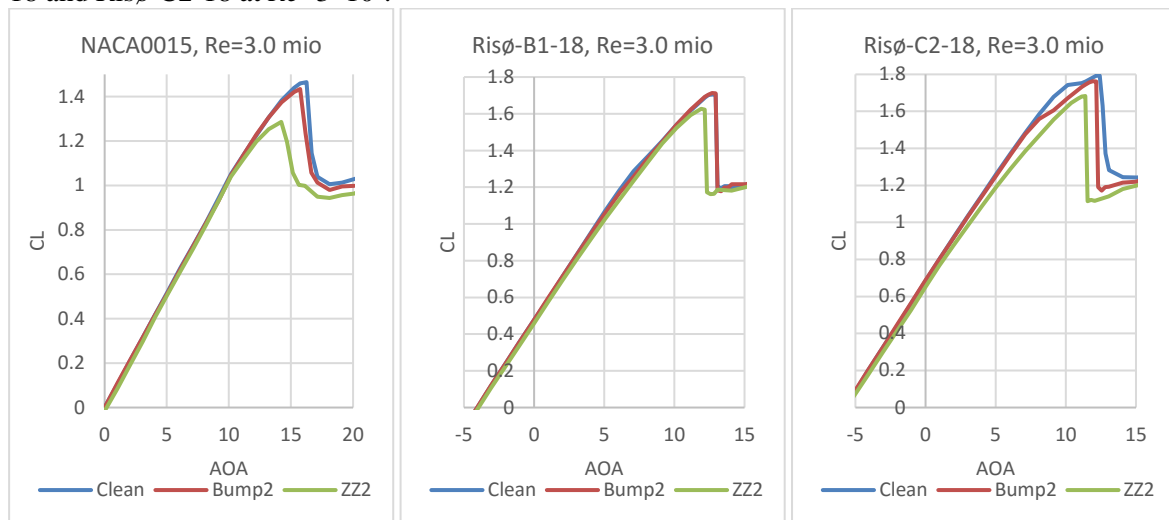

Figure 6 Lift coefficient as a function of AOA shown at Re = 3*10⁶ for three airfoils: NACA0015, Risø-B1-18 and Risø-C2-18.

For each plot three different configurations are seen: 1) Clean surface, 2) Bump tape at x/c=2% on suction side (h/c=110*10⁻⁶) and 3) Zigzag tape at x/c=2% on suction side (h/c=440*10⁻⁶). Analyzing the performance with bump tape (Bump2), there is no (or possibly a very small) influence on maximum lift. However, the zigzag tape (ZZ2) has a significant influence on the maximum lift, where reductions in the lift coefficient between 0.09 and 0.19 are seen. Therefore, from these measurements it can be seen that the maximum lift is influenced at $Re = 3*10^6$ if the bump height is more than h/c=110*10⁻⁶ and less than h/c=440*10⁻⁶. This is reflected in the plot in Figure 7 which is similar to the plot in Figure 5.
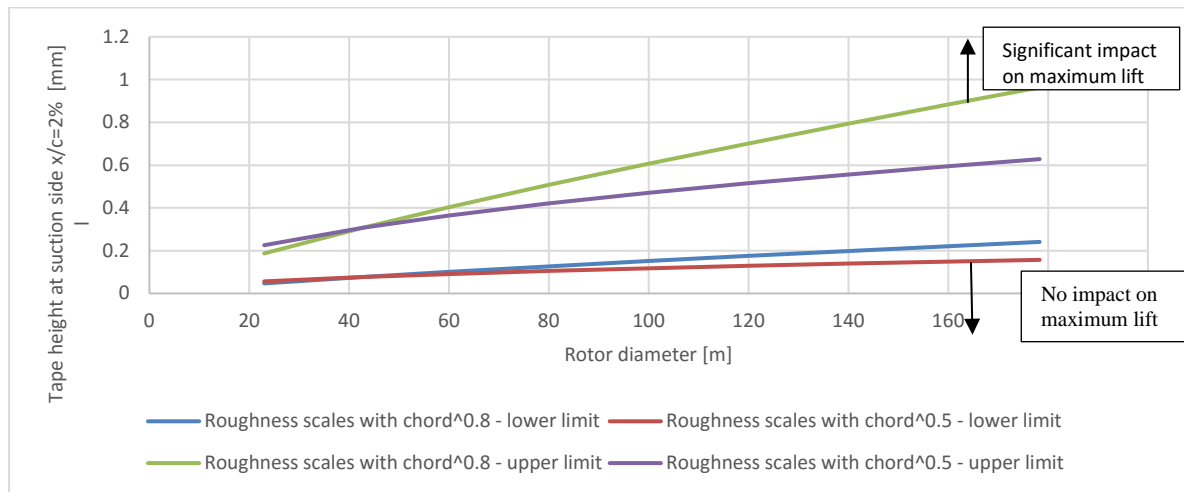
Figure 7 Bump/zigzag tape height on suction side at x/c=2% and r/R=80.7% as a function of rotor diameter. Curves show the lower and upper limit of roughness for influencing maximum lift. For both lower and upper limit trends following $c^{0.5}$ and $c^{0.8}$ are shown.

The plot is based on a direct scaling of the *DTU-10MW-RWT* wind turbine where tip speed, pitch etc. are constant, the bump height (i.e. the lower limit of roughness reducing maximum lift) at *x/c*=2% and the zigzag tape height (i.e. the upper limit of roughness reducing maximum lift) at x/c=2% at *r/R*=80.7% can within orders of magnitude be predicted for different rotor sizes. Assuming that a 0.1mm bump tape is the lower limit for not influencing the maximum lift at *Re*=3.0*10^6 for an airfoil with chord 0.900 m, and assuming that a reduction of maximum lift is significant for *Re*=3*10^6 when using zigzag tape, the corresponding bump height is 0.08 mm and the zigzag tape height is 0.31 mm if the rotor diameter is 42.8 m. Assuming that the roughness height relates to the chord as shown by the analytical investigation ($\Delta \sim c^{0.5}$), the lower limit is e.g. 0.11 mm and the upper limit is 0.42 mm for an 80 m rotor corresponding to a 2MW wind turbine. If the roughness height relates to the chord as indicated by the measurements ($\Delta \sim c^{0.8}$), the lower limit is e.g. 0.13 mm and the upper limit is 0.51 mm for an 80 m rotor. Because this investigation is based on rather few measurements there are some uncertainties related to the trends. However, what is indicated is that the maximum lift will not be influenced by leading edge roughness below the *"$c^{0.5}$ – lower limit"* trend (red curve), and maximum lift will be influenced by leading edge roughness above the *"$c^{0.8}$ – upper limit"* trend (green curve). This is indicated by the text boxes in the plot.

4. Conclusion and outlook
In this paper the critical leading edge roughness height was analyzed in two cases: 1) where the lift-drag ratio (or drag) is not changed and 2) where the maximum lift is not changed. The analysis is based on wind tunnel measurements on the airfoils NACA0015, Risø-B1-18 and Risø-C2-18 and at three different Reynolds numbers with two different leading edge roughness tape heights. Firstly, an analysis was carried out based on the boundary layer theory by Thwaites. With this method a relation between boundary layer height and Reynolds number was established. It was found that the momentum thickness increased with the $Re^{0.5}$ and thereby the $chord^{0.5}$ because the tip speed is rather constant for most wind turbines. This relation was also validated using a panel code. Secondly, the wind tunnel measurements combined with panel code predictions of the boundary layer momentum thickness created the basis for determining the impact of roughness on the aerodynamic performance. The critical heights were related to the Reynolds numbers, where the tape height relative to the momentum thickness at *x/c*=2% was found to be between 2.4 and 3.5. The investigation indicated that the relation $chord^{0.8}$ instead of $chord^{0.5}$ as suggested by Thwaites method might describe the critical roughness height better. However, due to differences in the pressure gradients in the wind tunnel tests this result is uncertain. This is because the

ratio between tape thickness and momentum thickness was investigated at many different angles-of-attack, where the pressure gradient is favorable at low angles-of-attack and adverse at high angles-of-attack.

An order of magnitude analysis was made by scaling a wind turbine and approximate roughness heights were estimated as shown in Table 2. These numbers are approximated because they depend on the exact chord length and tip speed. It is seen that the bigger the rotor diameter (and thereby chord), the bigger the critical roughness height is possible. What is not reflected from the table is that the critical roughness height does not increase linearly but proportionally with the (rotor diameter)$^{0.5}$ or (rotor diameter)$^{0.8}$.

Table 2 Estimated critical roughness height depending on rotor size and depending on which characteristics that are investigated.

Rotor diameter [m]	No change in lift-drag ratio: Roughness height [mm]	No change in maximum lift: Roughness height [mm]	Significant reduction in maximum lift: Roughness height [mm]
23	<0.04	<0.05	>0.23
178	<0.12	<0.16	>0.96

The results in this paper are based on three airfoils, at three Reynolds numbers with three different surface configurations resulting in 27 wind tunnel tests. However, to form a more solid basis for the conclusions more wind tunnel tests are needed. Thus, for future wind tunnel tests three airfoils could be tested at several Reynolds numbers, using several tape heights and chord wise tape positions.

5. Acknowledgements

References

[1]   Hooker R.W. 1933 The aerodynamic characteristics of airfoils as affected by surface roughness *NACA-TN-457 Langley Memorial Aeronautical Laboratory, Washington*

[2]   van Rooij R.P.J.O.M. , Timmer W.A. 2003 Roughness Sensitivity Considerations for Thick Rotor Blade Airfoils *Journal of Solar Energy Engineering-transactions of the ASME Volume 125 Issue 4 pp. 468-478*

[3]   Timmer W.A., Schaffarczyk A.P., The effect of roughness at high Reynolds numbers on the performance of aerofoil DU 97 W-300-Mod *Wind Energy 2004, DOI 10.1002/we.136*

[4]   Sareen A., Sapre C.A., Selig M.S. 2014 Effects of leading edge erosion on wind turbine blade performance *Wind Energy Volume 17 Issue 10 pages 1531–1542*

[5]   Gaudern N. 2014 A practical study of the aerodynamic impact of wind turbine blade leading edge erosion *J. Phys.: Conf. Ser.* **524** 012031

[6]   White F.M. 1991 Viscous Fluid Flow *Second edition, McGraw-Hill inc.*

[7]   Drela M. 1989 XFOIL, An Analysis and Design System for Low Reynolds Number Airfoils. Low Reynolds Number Aerodynamics *Volume 54, In Springer.Verlag Lec. Notes in Eng.*

[8]   Abbot H, von Doenhoff A.E. 1958 Theory of wing sections including a summary of airfoil data *Dover Publications, Inc. New York*

[9]   Fuglsang P., Bak C. 2004 Development of the Risø wind turbine airfoils *Journal of Wind Energy, Volume 7, Issue 2 April/June 2004, Pages 145–162*

[10]   Bak C., Andersen P.B., Madsen H.A., Gaunaa M., Fuglsang P., Bove S. 2008 Design and Verification of Airfoils Resistant to Surface Contamination and Turbulence Intensity *AIAA-2008-7050, 26th AIAA Applied Aerodynamics Conference, 18-21 August 2008, Honolulu, Hawaii*

[11]   Bak C., Zahle F., Bitsche R., Kim T., Yde A., Henriksen L.C., Andersen P.B., Natarajan A, Hansen M.H. Design and performance of a 10 MW wind turbine *Wind Energy, To be submitted.*