Technical University of Denmark

DTU

Wind tunnel tests of an airfoil with 18% relative thickness equipped with vortex generators

Bak, Christian; Skrzypinski, Witold Robert; Fischer, Andreas; Gaunaa, Mac; Brønnum, Niels Fiil; Kruse, Emil K.

DTU Library
Technical Information Center of Denmark

PAPER • OPEN ACCESS

Wind tunnel tests of an airfoil with 18% relative thickness equipped with vortex generators

View the article online for updates and enhancements.

Related content

- Research of the leading edge separation vortex characteristics due to the inlet velocity shape
  Xiao-ming Chen, Xiao-qing Feng and Xiao-chun Hu

- Experimental and numerical investigation of the performance of vortex generators on separation control
  C M Velte, M O L Hansen and K Jønck

- The influence of wing twist on pressure distribution and flow topology
  J Kiefer, N N Sørensen, M Hultmark et al.

Wind tunnel tests of an airfoil with 18% relative thickness equipped with vortex generators

Christian Bak[1], Witold Skrzypiński[1], Andreas Fischer[1], Mac Gaunaa[1], Niels Fiil Brønnum[2], Emil K. Kruse[2]

[1]DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde, Denmark
[2]Power Curve, Stationsmestervej 81, 9200 Aalborg S, Denmark

chba@dtu.dk

Abstract. Vortex generators have in recent years been used extensively on pitch regulated wind turbines. A new trend has been to use vortex generators on thinner airfoils on the outer part of the blades. However, not much data is available for thin airfoils with vortex generators. That is the reason to carry out wind tunnel tests on a NACA 63$_3$-418 airfoil with 18% relative thickness in the Stuttgart Laminar Wind Tunnel. The airfoil was tested in clean condition, but also with leading edge roughness and different heights and different positions of the vortex generators. Results of the airfoil performance in terms of polars, maximum lift and lift-drag ratio are shown with focus on how the vortex generators influence the performance of the airfoil.

1. Introduction

Vortex generators (VGs) are aerodynamic devices that can delay separation and thereby increase the maximum lift for a wing. Already in the 1940s and 1950s this principle was investigated for airplanes, e.g. [1]. For wind turbines it was used for the stall regulated types as early as in the 1980s on the MOD-2 wind turbine [2] and later in the 1990s for the commercially available stall regulated wind turbines to increase the rated power, e.g. [3,4]. In around year 2000 the wind industry lost the interest in VGs in the process of changing control strategy from stall regulation to pitch regulation. Around ten years later they got a revival. Recently they have been used in retrofit to existing wind turbines. In recent years, installation of VGs on both the inner and outer part of rotors has been investigated. However, investigation of VGs has been focused on improvement of the performance of thick airfoils and only limited knowledge about performance of thinner airfoils equipped with VGs exists. VGs on thick airfoils, i.e. on the inner part of rotors, are needed to increase the maximum lift that often is low because of leading edge roughness (LER) or because of the inherently separated regions on thick airfoils that the VGs can remedy. VGs on thinner airfoils are mainly used to obtain a reliable maximum lift despite of the LER that can appear either because of erosion/wear and tear, because of dust/bugs and other contamination or because of deviations in the shape of the manufactured blades. In recent years VGs on the outer part of rotors have been installed on both new wind turbines or as a retrofit for existing wind turbines. This is done because it has been realized that the Annual Energy Production (AEP) can be increased by the use of VGs as described by manufacturers e.g. Siemens-Gamesa [5]. In a project in cooperation between the company Power Curve and DTU, the retrofit of vortex generators was investigated. In this project installation of VGs on both the inner and outer part of rotors was analyzed, where tools for prediction of performance were developed and used [6] and also measurements were carried out. VG designs made in the project were tested on existing commercially operated wind turbines

and showed improved results for the AEP in good agreement with the predictions [7]. Further to this, a Vestas V52 850kW pitch regulated variable speed wind turbine, which is used as a research wind turbine at DTU Risø Campus, was equipped with vortex generators with an aggressive VG layout and was tested to reveal the changes in blade loading [8]. When designing the layout of the VGs on the blades, reliable data for airfoils with and without VGs and with and without LER is of major importance. Since there was no such data available for airfoils with relative thickness smaller than 24%, wind tunnel tests were carried out to provide such data.

In this paper wind tunnel measurements on a NACA 63_3-418 airfoil that has a relative thickness of 18% are described. This airfoil was commonly used for wind turbine blades until a decade ago. In this paper the relations between key performance indicators such as maximum lift and lift-drag ratio and VG position as well as VG height both in the case of a clean airfoil and an airfoil with LER are investigated.

2. Method

To investigate the performance of the NACA63_3-418 airfoil with and without VGs and LER, wind tunnel tests were carried out in the Stuttgart Laminar Wind Tunnel [9]. With a cross sectional area of H*W = 0.73m*2.73m, a chord length of c=0.600m and a flow speed of 75m/s, a Reynolds number of 3 million was obtained. The lift was determined by experimental integration of the pressure distribution along the two opposite walls facing the suction and pressure sides, respectively. The drag was measured using a wake rake. At high angle-of-attack the wake rake was not used because of violent vibrations induced by the flow so the drag must be determined from the pressure measurements. All drag values shown in this paper are based on the wake rake measurements.

Figure 1 The NACA 63_3-418 airfoil mounted in the test section with VGs and LER mounted at the surface.

In the analysis of the NACA 63_3-418 airfoil, geometry data of the scanned airfoil was used. The airfoil chord was for the measured geometry defined from the leading edge to the trailing edge, where the coordinates for the theoretical shape are defined differently with a chord that has a starting point slightly below the leading edge and an ending point at the trailing edge. This difference in the definition results in a difference in the angle-of-attack of around 0.28 degrees. The airfoil was tested with VGs of two different heights provided by Power Curve, and with and without LER in the form of zigzag tape. The higher VGs, with a nominal height of $h = 5$mm are positioned on a 23mm wide plastic strip with a thickness of 1.1mm. The total height of the VGs including the mounting strip is 6.1mm. From the side view, the shape of the VG is a triangle. The smaller VGs (a scaled version of the higher ones) have a nominal height of $h = 2.5$mm and the same base plate as the larger ones. The total height of this VG including its mounting strip is 3.5mm.
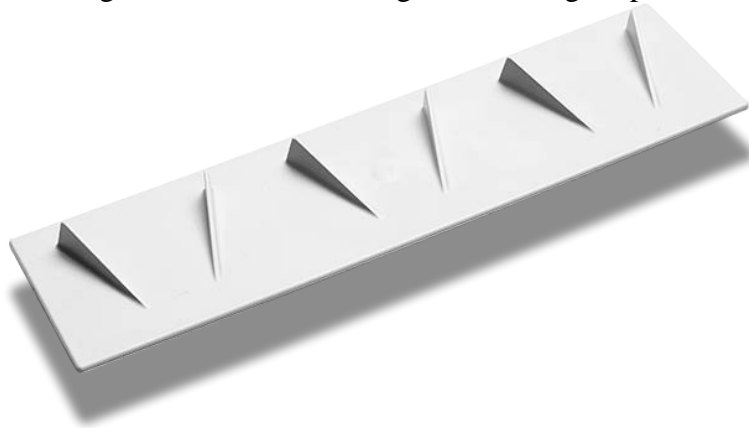

Figure 2 The vortex generators used for the tests.

The test matrix was arranged so that VGs were mounted in different chordwise positions to compensate for performance with LER. In this way variations in the lift as a function of VG position were investigated. During the measurement campaign the data was analyzed so that decisions about positioning of the VGs could be made.

3. Results
A plot of the performance with and without VGs with a height of 2.5mm is shown in Figure 3, where the lift coefficient (c_l) as a function of the drag coefficient (c_d) is shown to the left and c_l as a function of angle-of-attack (α) is shown to the right. Four different configurations are seen: 1) The clean case with no LER or VGs, 2) the LER case where LER is simulated by using zigzag tape, 3) the case where VGs are mounted at the suction side at a chord length of 30% with an otherwise clean surface and 4) the same as 3), but with LER. From this plot it is clear that LER reduces the maximum lift significantly from 1.4 to 1.15, but also that VGs can limit this reduction. Mounting 2.5mm VGs at 30% chord length will result in an almost unchanged maximum lift. With VGs mounted at 30% chord length and with no LER a significant increase in maximum lift of up to 0.48 is observed. The VGs will add extra drag at lower lift values, but will reduce the drag at higher lift values when comparing to the clean case or the LER case. The mechanism behind this behavior is the suppression of stall and the associated pressure drag. In clean conditions the VGs will add an extra drag of around Δc_d=0.0045 and with LER the VGs will add an extra drag of around Δc_d=0.0030. It is seen that after the regions where the VG's can modify the lift, the lift values fall back to the lift values of the respective non-VG cases. So after a certain angle of attack, the VG's have no aerodynamic effect. This is most likely when the VG's themselves get inside the separation zone.
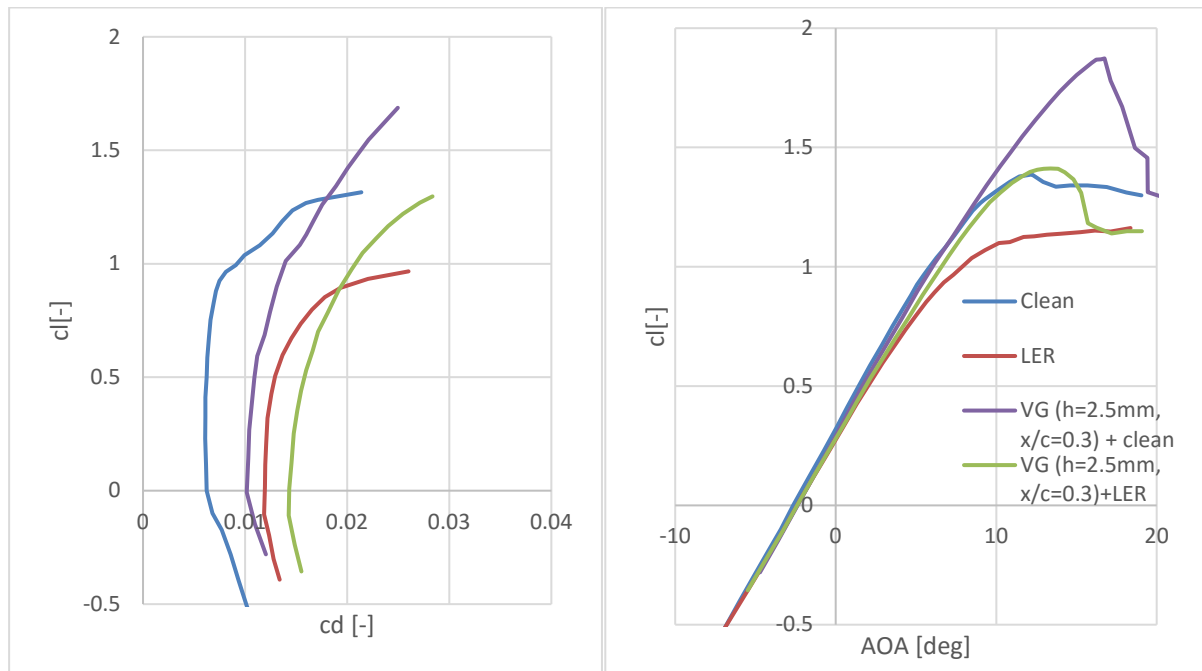
Figure 3 The NACA63$_3$-418 airfoil in four different configurations: 1) Clean surface, 2) LER (zigzag tape), 3) Clean and VG positioned 30% from the leading edge and 4) LER and VG positioned 30% from the leading edge.

Pressure distributions corresponding to the polars shown in Figure 3 are shown in Figure 4 at an angle-of-attack around 10 deg. The regions where the flow is stalling on the suction sides of airfoils have the distinct feature that the pressure is almost constant. It is clear that there is almost no separation close to the trailing edge in clean conditions whereas separation is present from around x/c=0.6 if LER is found on the airfoil. With VGs mounted the pressure distribution will be restored with LER on the airfoil and if LER is not on the airfoil the pressure on the suction side is slightly lower and there is no separation close to the trailing edge. The lift coefficients for the four configurations are c_l=1.26 (clean), 1.03 (LER), 1.35 (clean+VG) and 1.22 (LER+VG).

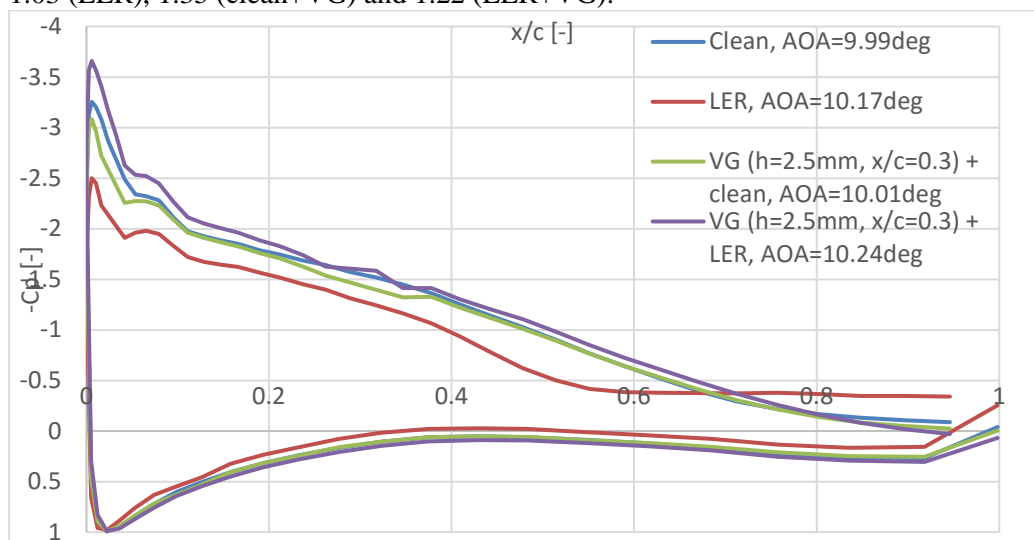**Figure 4 Pressure distributions for the NACA63$_3$-418 airfoil in four different configurations: 1) Clean surface, 2) LER (zigzag tape), 3) Clean and VG positioned 30% from the leading edge and 4) LER and VG positioned 30% from the leading edge.**

The performance with and without VGs with a height of 5mm is shown in Figure 5, where the lift coefficient (c_l) as a function of the drag coefficient (c_d) is shown to the left and c_l as a function of angle-of-attack (α) is shown to the right. Five different configurations are seen: 1) The clean case with no LER or VGs, 2) the LER case where LER is simulated by using zigzag tape, 3) the case where VGs are mounted at the suction side at a chord length of 50% with an otherwise clean surface, 4) the case where VGs are mounted at the suction side at a chord length of 60% with LER and 5) the same as 3) i.e. VGs at 50% chord length, but with LER. Again, it is clear that VGs can limit the reduction in maximum lift that is a result of LER. Mounting 5mm VGs between 50% and 60% chord length will result in an almost unchanged maximum lift. With VGs mounted at 50% chord length and with no LER a significant increase in maximum lift of the same amount as in Figure 3 up to 0.48 is observed. However, the 5mm VGs show a somewhat more abrupt loss in lift in the post stall region, where the lift value drops to that of the respective non-VG case. Also, around maximum lift a static hysteresis loop appeared with high maximum lift when the angle-of-attack was increased and with a lower maximum lift when the angle-of-attack was decreased. Furthermore, similar to the plots in Figure 3 the VGs will add extra drag at lower lift values, but will reduce the drag at higher lift values when comparing to the clean case or the LER case. In clean conditions the VGs will add an extra drag of around Δc_d=0.0045 and with LER the VGs will add an extra drag of around Δc_d=0.0030. This extra drag is the same as for the smaller 2.5mm VGs.
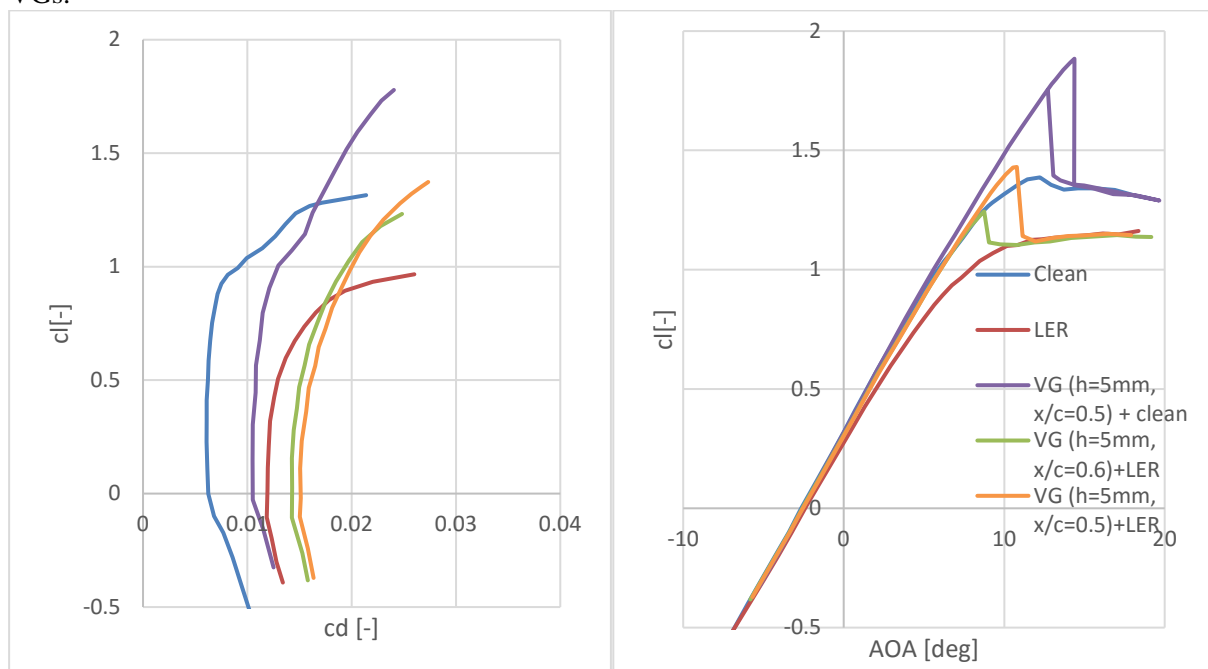

Figure 5 The NACA63$_3$-418 airfoil in four different configurations: 1) Clean surface, 2) LER (zigzag tape), 3) LER and VG positioned 60% from the leading edge and 4) LER and VG positioned 50% from the leading edge.

Several tests were carried out with different positions and sizes of VGs. Based on these tests the variations in maximum lift and maximum lift-drag ratio are shown in Figure 6 and Figure 7. Maximum lift and maximum lift-drag ratio as a result of the mounted VGs are seen relative to maximum lift and maximum lift-drag ratio for a clean airfoil. In the plots the performance with only LER and no VGs are also seen as a reference. From Figure 6 it is seen that if LER is present on the airfoil VGs can regain the maximum lift for a clean airfoil if VGs with a height of 2.5mm are mounted at x/c≈0.34 or if VGs with a height of 5mm are mounted at x/c≈0.52. If there is no LER on the airfoil, VGs with a height of 2.5mm and mounted at x/c≈0.34 will result in a maximum lift 0.46 higher and a lift-drag ratio 46 lower than in clean conditions. If VGs with a height of 5mm are mounted at x/c≈0.52 the maximum lift will in this

case also be 0.46 higher than in clean conditions and the lift-drag ratio will be 44 lower. If no VGs are mounted a loss in maximum lift of 0.22 is observed. Furthermore, the maximum lift-drag ratio for the airfoil with LER and VGs with height 2.5mm and mounted at x/c≈0.34 is 73 lower than in clean conditions. If 5mm VGs are mounted at x/c≈0.52 with LER the maximum lift-drag ratio is 70 lower. Thus, both the change in maximum lift and change in the maximum lift-drag ratio are marginally different for the two different VG heights mounted at different chordwise positions with and without LER. If no VGs are mounted a loss in maximum lift-drag ratio of 75 is seen.
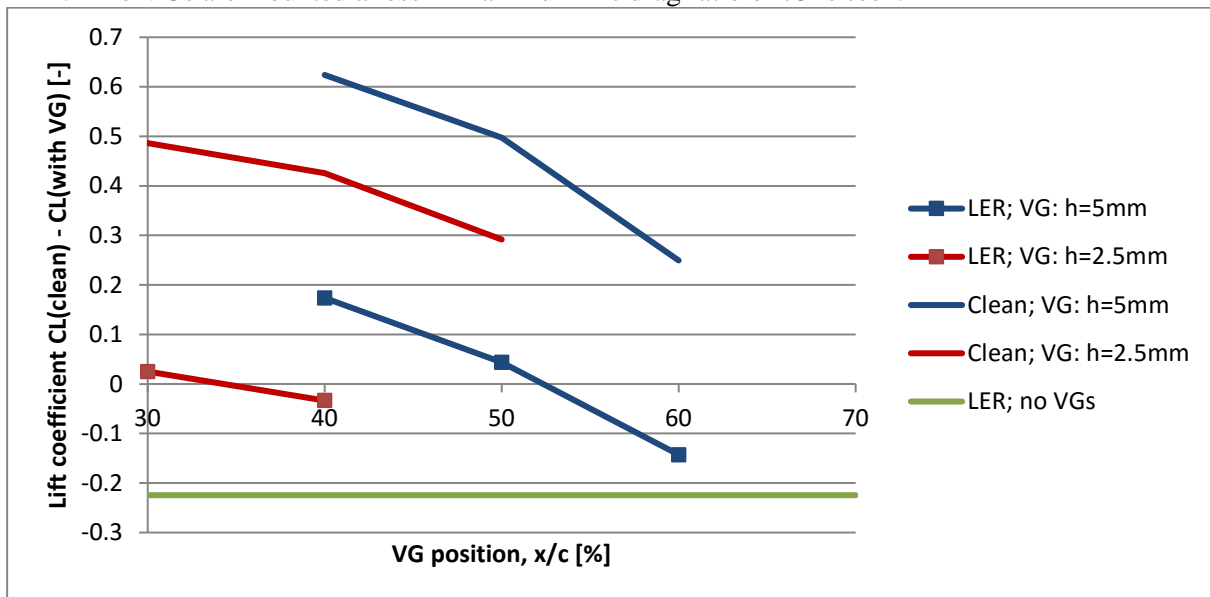

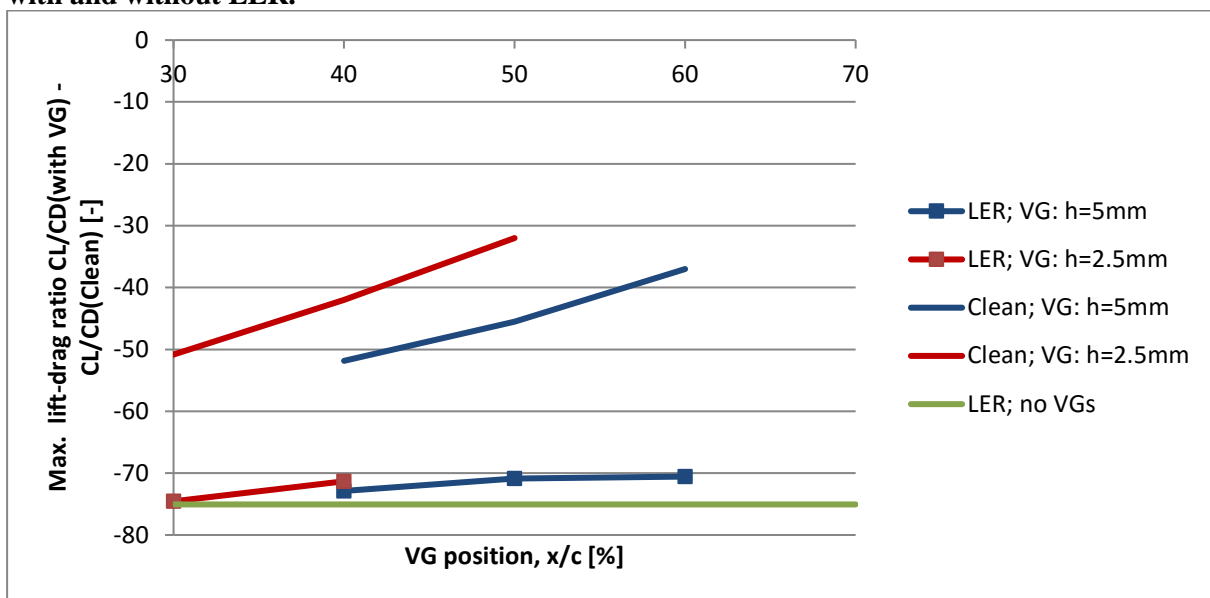**Figure 6 Difference in maximum lift coefficient (c_l(VG)-c_l(clean)) as a function of VG position and with and without LER.**

Figure 7 Difference in maximum lift-drag ratio (c_l/c_d(VG)- c_l/c_d(clean)) as a function of VG position and with and without LER.

4. Discussion

The traditional way of mounting VGs is to enhance the performance of thick airfoils where the aerodynamic performance is sensitive to e.g. leading edge roughness and where the maximum lift without the use of VGs often is low. Mounting VGs on the outer part of rotors is not common, but is an emerging way of controlling the aerodynamics. One reason to do this is to decrease the influence of LER. As shown in Figure 8 the lift-drag ratio is affected by the LER and the VGs. The local power coefficient for a wind turbine rotor can be estimated by the use of a method described by Bak [10] using the formula $CP_{loss,local} = \frac{3}{2}\frac{\lambda_{local}}{c_l/c_d}$. This formula can estimate the loss that is experienced comparing to the situation with inviscid flow, e.g. when there are no losses and $c_l/c_d=\infty$. Operating a wind turbine at a lift coefficient of 0.95, which is at the lower end of a likely design lift range, the local power efficiency, $CP_{loss,local}$, can be estimated based on the plots in Figure 8. This is shown in Table 1.

From the plots in Figure 8 (left) and from Table 1 it is seen that c_l/c_d is 120, 40, 70 and 47 in the case of clean, LER, VG(2.5mm, x/c=0.3, clean) and VG(2.5mm, x/c=0.3, LER), respectively. In the clean case (c_l/c_d=120) there will be a loss of 8.8% if λ_{local}=7. With a tip speed ratio of e.g. 9 λ_{local}=7 corresponds to 78% of the rotor radius. The losses will be 26.3%, 15.0% and 22.3% for the LER case, VG (clean) and VG (LER), respectively. Compared to the clean case the losses in local CP will then be 17.5%, 6.3% and 13.6%, respectively. It is important to emphasize that these losses are for the local CP and that reduced efficiency due to tip losses, root losses etc. are not included. Thus, the losses are only estimated for a single point of operation well below rated wind speed. In this case the VGs do not result in larger losses. On the contrary the VGs improve the efficiency. However, the loss in maximum lift due to LER can result in a loss in power at wind speeds slightly less than rated wind speed. The VGs will avoid a significant loss in maximum lift which again can avoid a critical loss in the power performance. Losses corresponding to the plots in Figure 8 (right) are similar to the losses described above. Thus, even though the lift-drag ratio is lowered by the VGs at low lift coefficients the benefit from the significant higher lift-drag ratio at higher lift coefficients is important.
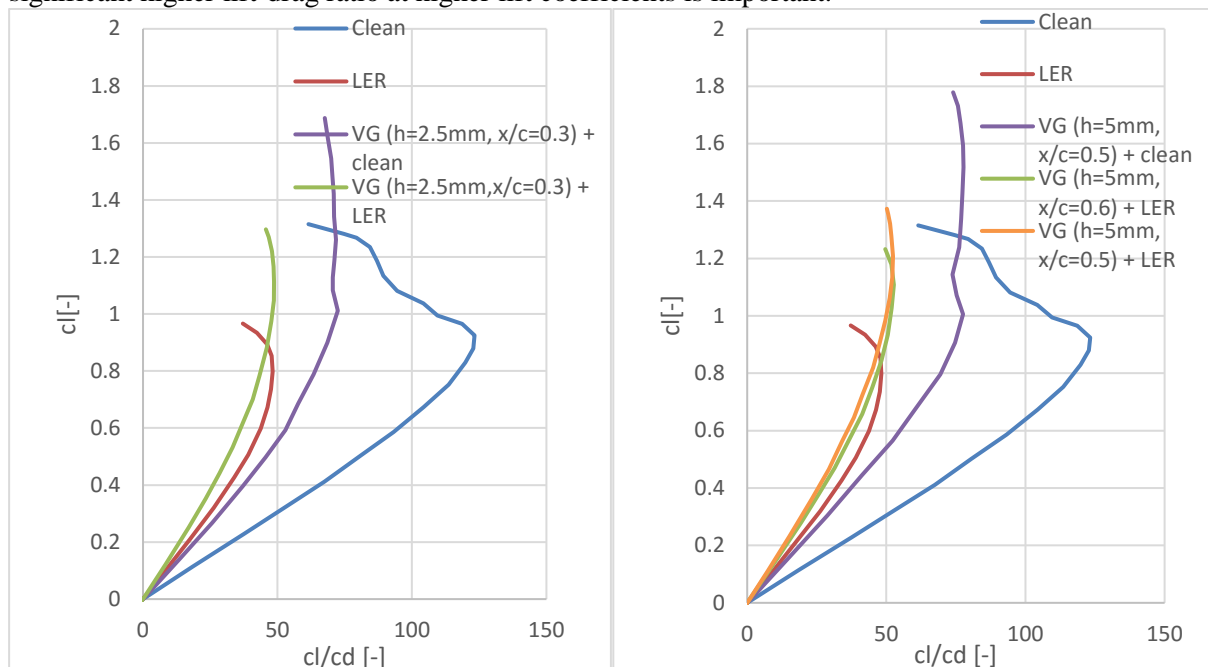

Figure 8 The lift coefficient for the NACA63₃-418 airfoil as a function of the lift-drag ratio in the case of 1) 2.5mm VGs at x/c=0.3 (left) and 2) 5mm VGs at x/c=0.5 and 0.6. The configurations correspond to the plots in Figure 3 and Figure 5, respectively.

Table 1 Estimated losses in local power efficiency.

Configuration	cl/cd@cl=0.95	$CP_{loss,local}$ @λ_{local}=**7** [%]	$CP_{loss,local}$ - $CP_{loss,local,clean}$ [%]
Clean	120	8.8	0
LER	40	26.3	17.5
VG(2.5mm, x/c=0.3, Clean)	70	15.0	6.3
VG(2.5mm, x/c=0.3, LER)	47	22.3	13.6
VG(5mm, x/c=0.5, Clean)	76	13.8	5.1
VG(5mm, x/c=0.6, Clean)	51	20.6	11.8
VG(5mm, x/c=0.5, LER)	49	21.4	12.7

5. Conclusion

Even though the measurements with VGs and LER are only carried out for one airfoil and for a limited number of configurations, the measurements indicate some correlations. The following important observations are made for the NACA 63_3-418 airfoil:

- VGs can compensate the loss in maximum lift caused by LER
- VGs decrease the drag at higher angles of attack as a result of the higher maximum lift. This implies that the power curve at wind speeds close to rated power are increased and thereby that the AEP can be increased significantly by positioning the VGs correctly.
- VGs increase the drag at low angles of attack. This imply that the power curve at low wind speeds are reduced and thereby that a small part of the AEP is lost. However, in general the gain in AEP at higher wind speeds is higher than the loss in AEP at lower wind speeds [8].
- The increase in drag at low angles of attack is bigger for a clean airfoil than for an airfoil with LER. However, since a clean airfoil is idealized and implies that the surface is very smooth from the factory, that there is no bugs/dust at the leading edge, that there is no erosion/wear and tear, "clean" conditions will only appear when the blade is brand new. After a short time that depends on the site the blade is not clean any more, and a certain level of LER must be expected.
- The bigger 5mm VGs should be positioned 0.18c further downstream of the smaller 2.5mm VGs to obtain the same increase in maximum lift. This is true for an airfoil both with and without LER.
- The 5mm VGs positioned at 0.52c show almost the same loss in lift-drag ratio with and without LER (70 and 46, respectively) as the 2.5mm VGs positioned at 0.34c (73 and 46, respectively)
- The 5mm VGs positioned at 0.5c on an airfoil with and without LER show a more abrupt stall behaviour than the 2.5mm VGs positioned at 0.3c.

Estimating the effect of LER measured in the wind tunnel on a radial position of a rotor with λ_{local}=7 and operating at a lift coefficient of 0.95 a loss in local power efficiency of 17.5% is seen compared to a clean airfoil. If VGs are installed, the performance will improve slightly to a loss of 13.6%. It should be emphasized that this reduction in loss is seen at a lift coefficient of 0.95 that is for operating conditions well below rated power. Thus, installing VGs on a blade with a certain amount of LER VGs will in general increase the power when the blades are operated at higher angles of attack, i.e. just below rated wind speed.

6. References

[1]   McFadden, N.M.; Rathert sr., G.A., Bray, R.S.; The effectiveness of wing vortex generators in improving the maneuvering characteristics of a swept-wing airplane at transonic speeds; NACA RMA51J18, 1952

[2]   Sullivan, T.I., Effect of Vortex Generators on the Power Conversion Performance and Structural Dynamics Loads of the MOD-2 Wind Turbine, NASA TM, 83680, 1984

[3]   Griffin, D.A.; Investigation of Vortex Generators for Augmentation of Wind Turbine Power Performance; NREL/SR-440-21399, UC Category 1210, DE97000087; 1996

[4]   Peter Fuglsang, Ioannis Antoniou, Kristian S. Dahl, Helge Aa. Madsen; Wind Tunnel Tests of the FFA-W3-241, FFA-W3-301 and NACA 63-430 Airfoils; Risø-R-1041(EN); Risø National Laboratory, Roskilde, 1998

[5]   Leaflet 'Siemens Power Curve Upgrade', E50001-D530-A119-X-7600 SWP Power Curve Upgrade Product Sheet (https://www.energy.siemens.com/us/pool/hq/power-generation/renewables/wind-power/PowerUpgrade.pdf, checked 4 May 2018)

[6]   Skrzypinski, W.R; Gaunaa, M.; Bak, C.; The Effect of Mounting Vortex Generators on the DTU 10MW Reference Wind Turbine Blade. In: Journal of Physics: Conference Series (Online), Vol. 524, No. 1, 012034, 2014.

[7]   Skrzypiński; W.R.; Gaunaa, M.; Bak, C.; Brønnum, N.F.; Olsen, E.B.K.; Increase in the Annual Energy Production due to a Retrofit of Vortex Generators on Blades; AWEA Wind Power Conference & Exhibition 2015, Orlando, Florida, May 18-21

[8]   Christian Bak, Witold Skrzypiński, Mac Gaunaa, Héctor Villanueva, Niels F. Brønnum, Emil K. Kruse, Full scale wind turbine test of vortex generators mounted on the entire blade, In: Journal of Physics: Conference Series (Online), Vol. 753, 022001, 2016.

[9]   Würz W, Vetter C, Langohr-Kolb M. Wind Tunnel Measurements of the NACA 63_3-418 Airfoil with Vortex Generators, Institut für Aerodynamik und Gasdynamik, Universität Stuttgart, Stuttgart, February 2015

[10]   Christian Bak, Aerodynamic design of wind turbine rotors, Advances in Wind Turbine Blade Design and Materials — 2013, edited by Brøndsted, Povl; Nijssen, Rogier, Woodhead Publishing