Final report

1. Project details

Project title	AdvancedVG
File no.	64019-0517
Name of the funding scheme	EUDP
Project managing company / institution	DTU Wind and Energy Systems
CVR number (central business register)	30 06 09 46
Project partners	PowerCurve, LM Wind Power and HOFOR
Submission date	23 April 2024

2. Summary

(In English):

The goal of this project was to develop an improved Vortex Generator (VG) geometry and layout on wind turbine blades. After an initial patent search two new VG geometry ideas ("Cascade" and "Ship") were proposed and tested in the wind tunnel at LM Wind Power and compared to numerous known VG geometries. Both new ideas showed very promising result in terms of drag reduction compared to State-of-the-Art (SoA), but since it was desired that the new geometry should be plastic injection molded the so called "Cascade" was for practical reasons chosen for further optimization and for the final in situ side-to-side validation. A patent claim has been made and this geometry is advertised on PowerCurve's homepage.

(In Danish):

Målet med projektet var at udvikle en forbedret VG geometri og dennes layout på vindmølleblade. Efter en indledende patentsøgning blev to nye geometrier ("Cascade" og "Ship") foreslået og efterfølgende testet i LM Wind Powers vindtunnel og sammenholdt med kendte VG geometrier. Begge forslag viste potentiale mht. at nedbringe vindmodstanden sammenholdt mod state-of-the-art (SoA), men "Cascade" geometrien blev valgt til videre optimering og til det endelige in-situ fuldskalaforsøg, da den valgte geometri helst skal kunne sprøjtestøbes i en senere masseproduktion. Der er indleveret en patentansøgning og PowerCurve er begyndt at reklamere for den nye VG på deres hjemmeside.

3. Project objectives

The objective of this project was to increase long-term efficiency of new and existing wind turbine blades by reducing the amount of stall in the root-region (due to thick airfoils) and by decreasing their sensitivity to contamination and erosion. This will be achieved by the development of innovative low-drag vortex generators, and the development of improved methods to place them optimally on the blade.

At the beginning of the project a patent search was initiated with the purpose to see what geometries and ideas are already protected by IPR. Two new ideas were proposed, a multielement airfoil denoted “Cascade”, see Figure 1, and a delta wing shaped VG called “Ship”, see Figure 2.

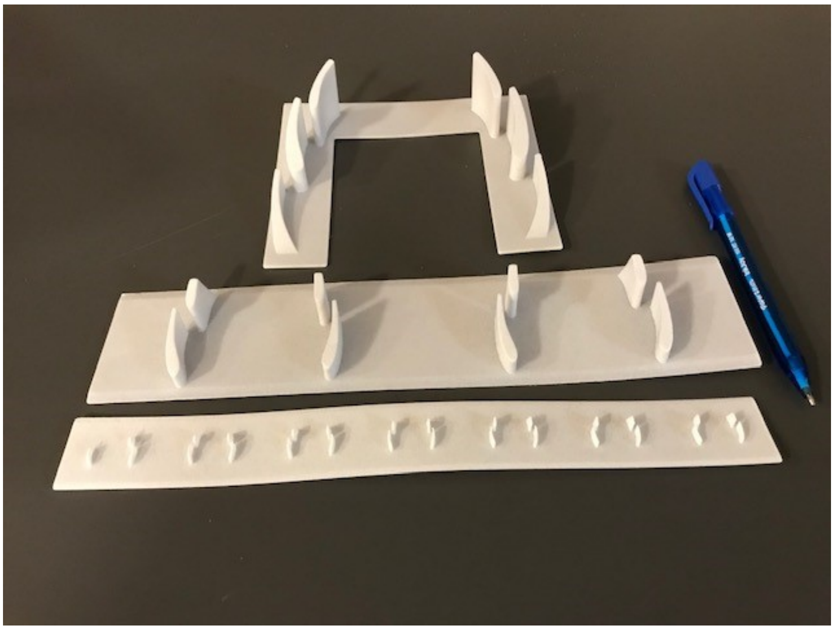

Figure 1: *Samples of “Cascade” VGs*

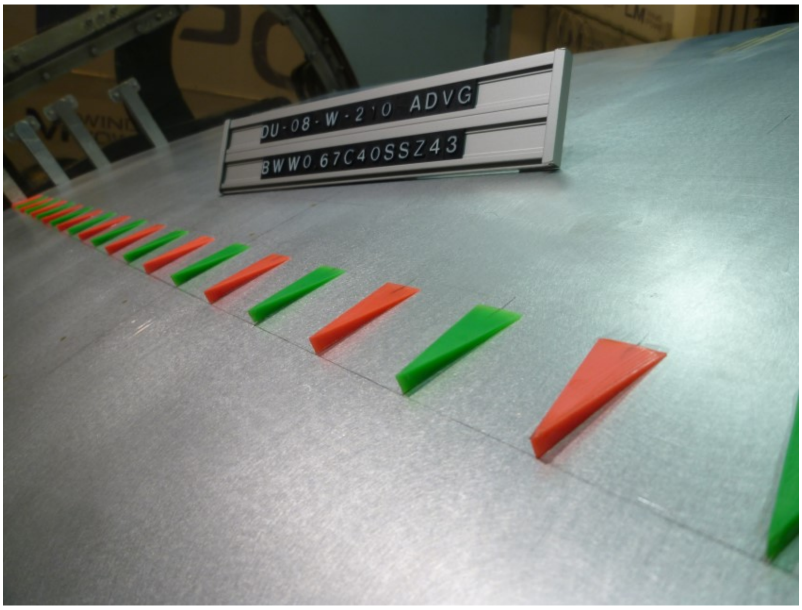

Figure 2: *The “Ship” VG mounted on the airfoil in the wind tunnel at LM Wind Power*

4. Project implementation

WP1: Project management

The program was managed by Martin O.L.Hansen, DTU Wind and Energy Systems and a steering committee comprised by Jesper Madsen, LM Wind Power, Kenneth Thomsen, DTU Wind and Energy Systems and Niels Brønnum, PowerCurve was formed at the beginning of the project. The progress and how to proceed the next period was discussed at regular steering committee meetings.

WP2: Quantifying gains of innovative Vortex Generators

In the very beginning a patent search was initiated to avoid getting into conflict with existing patents and to avoid spending time investigating concepts that had already been studied. Two new geometries suggested by the project participants, Figures 1 and 2, were then chosen for assessment of potentials by comparing to SoA. After some initial CFD computations as e.g. shown in [1] and in Figure 3 the geometries were 3-D printed and tested in the wind tunnel at LM Wind Power. There was of course some risk that the new VGs would not perform better than the triangular SoA Vortex generators as shown in Figure 4. For the delta wing VG the lift to drag ratio was better than SoA and the CFD results agreed quite well with the wind tunnel measurements. Also, the "Cascade" performed really well compared to SoA. All wind tunnel measurements in WP2 were made in the wind tunnel at LM Wind Power using the DU08-W-210 airfoil at a Reynolds number of 5 million. The VGs were placed at 40% chord and the VG height was 0.7% of the airfoil chord for both the standard VG and the Cascade. Further the VG spacing was also the same for the measurements to allow for a direct comparison. It was shown that the cascade VG has the same beneficial effect on the lift as the standard VGs and that this happens at a lower drag. The lift to drag ratio of the Cascade VGs at the design angle of attack of 7 degrees increased compared to SoA VGs 15% and 10% for the clean and the rough configuration simulated using zig zag tape, respectively. Both the Cascade VG and the delta wing (Ship) VG show a better performance than the standard SoA VGs. It was, however, decided after a steering committee meeting to focus only on the Cascade VG, since mass production using plastic injection moulds is really difficult for the Ship VG geometry. This WP ended successfully since it was validated in the LM Wind Tunnel that the new VGs are better in terms of a lower drag penalty for the same increase in lift

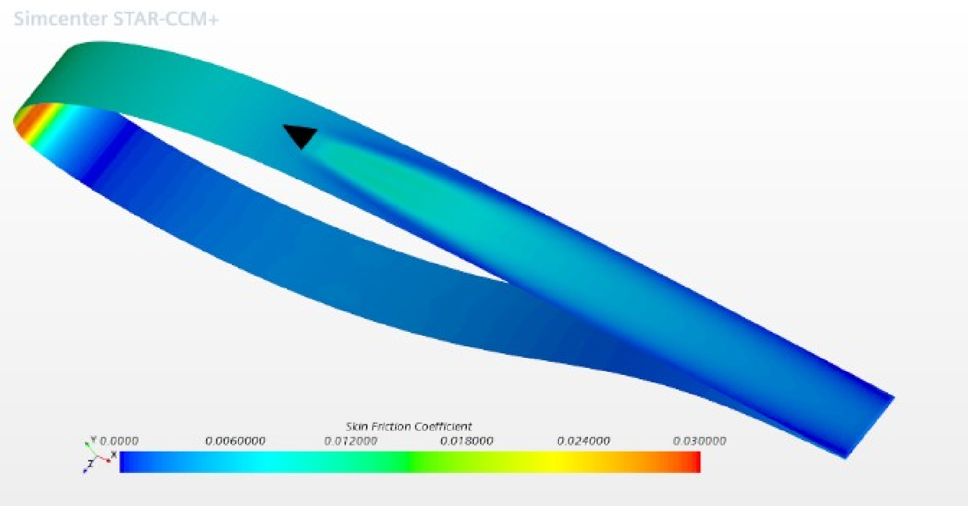

Figure 3: *CFD computation from [1] of the delta wing VG mounted on a DU08-W-210 airfoil at an angle of attack of 12°, fully turbulent. The colours show the skin friction at the surface, and it is seen that this is increased behind the VG indicating a higher momentum of the boundary layer flow and thus a resilience to flow separation in the adverse pressure gradient.*

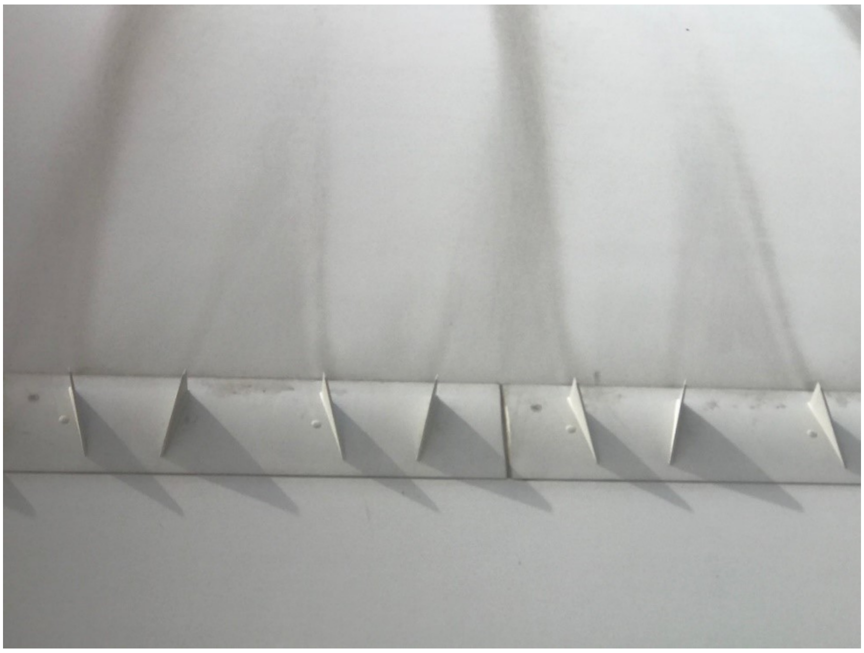

Figure 4: *Photo of state-of-the art triangular Vortex Generators mounted on a wind turbine blade*

WP3: Improvements in numerical modelling of blades with LER and/or VGs

In this WP a new wind tunnel campaign was made in the Poul La Cour (PLC) wind tunnel at DTU Wind and Energy Systems. It was decided to test the use of VGs near the blade root characterized by very thick airfoils. At a steering committee meeting it was decided to use a 35% thick DU profile since this airfoil is utilized on many commercial wind turbine blades. A physical model made for the PLC tunnel was ordered from Designcraft and shown in Figure 5. The shell is made of carbon fibre instead of aluminium to enable measuring transition. Unfortunately, it turned out that the final price was 60.000 kr more than specified in the original budget, so it was necessary to apply EUDP for a re-budget and luckily this was partly covered by a slightly lower hourly rate using the PLC wind tunnel. Also, a pressure sensitive paint system was tested in the PLC tunnel with the aim to determine the spanwise effect of individual VGs, but the results were not very promising. However, the system is presently at LM Wind Power, who is now assessing the potential use in their own wind tunnel.

PowerCurve carried out significant development of CFD processes, especially around the modelling of a full rotor in 3D with VGs. Meshing and solving techniques were developed, tested, and optimised leading to a final simulation setup "philosophy" being finalised. A commercial code, Siemens SimCenter StarCCM+ was utilised for this work. The results of this work package were then used in WP4 to design the field trial layout on the Vestas V80 turbine – see figures 8 and 9.

Considerable effort was also used to establish an automated pseudo-2D CFD simulation methodology to rapidly evaluate large numbers of VG geometry variants at the aerofoil level. This allowed over 40 unique geometries to be assessed and enable objective down-selection for wind tunnel testing.

Figure 5: *The 35% thick DU airfoil model ordered at Designcraft for the PLC wind tunnel tests*

The main results from the PLC wind tunnel measurements are: The baseline configuration, i.e. without any VGs, performs very bad in rough configuration modelled by zig zag tape. This is somewhat better in a clean configuration, but since blades degrade and become dirty over time this will not always be the case, but luckily VGs can cure this. The lift to drag ratio applying the cascade VG really improves the efficiency of this very thick airfoil and is even better than without any VGs. For an operational angle of attack of 8 degrees in clean configuration, without roughness, the cascade VG geometry denoted B (having two airfoils) increases the glide ratio (lift-drag) with as much as 35 % and 8% for the cascade geometry denoted A having three airfoils (see also Figure 1). The improvement in the rough configuration modelled by zig zag tape is 7% compared to SoA for cascade geometry A. So also, for the thick airfoil the Cascade VGs outperforms the SoA triangular VG geometry with respect to both maximum lift and lift to drag ratio.

Before it was allowed to mount and test the VGs on the 2MW Vestas wind turbines owned and operated by HOFOR it was required to justify that the VGs will not change the stability and the loads in a way that may influence the safety of the turbines. This was done using HAWC2 simulations and changing the airfoil data to include the effect of the VGs. A worst-case scenario was chosen where VGs are placed all along the blades and the airfoil data (lift and drag as function of angle of attack) needed as input to HAWC2 were a combination of the wind tunnel data and CFD. Figure 6 shows the main result from simulating ultimate loads for load cases DLC1.1 (normal turbulence, operational wind speed range) and DLC1.3 (extreme turbulence, operational wind speed range). Explanation to the Figure

TB FA	Tower base fore-aft moment
TT Tilt	Tower top tilt moment
Flap BRM	Flapwise root bending moment

TB SS Tower base side-to-side moment
TT roll Tower top roll moment
Edge BRM Edgewise blade root bending moment
Shaft tor. Shaft torsion
Thrust Thrust, Axial force

For DLC1.1 the ultimate thrust and blade root flapwise moment increases 5%. For DLC1.3 only the TB SS and edgewise root bending moment increases less than 2%, and this is within acceptable bounds to allow us to mount VGs on HOFOR's Vestas turbines. This also goes for the fatigue analysis from DLC1.2 (normal turbulence, operational range) not shown here.

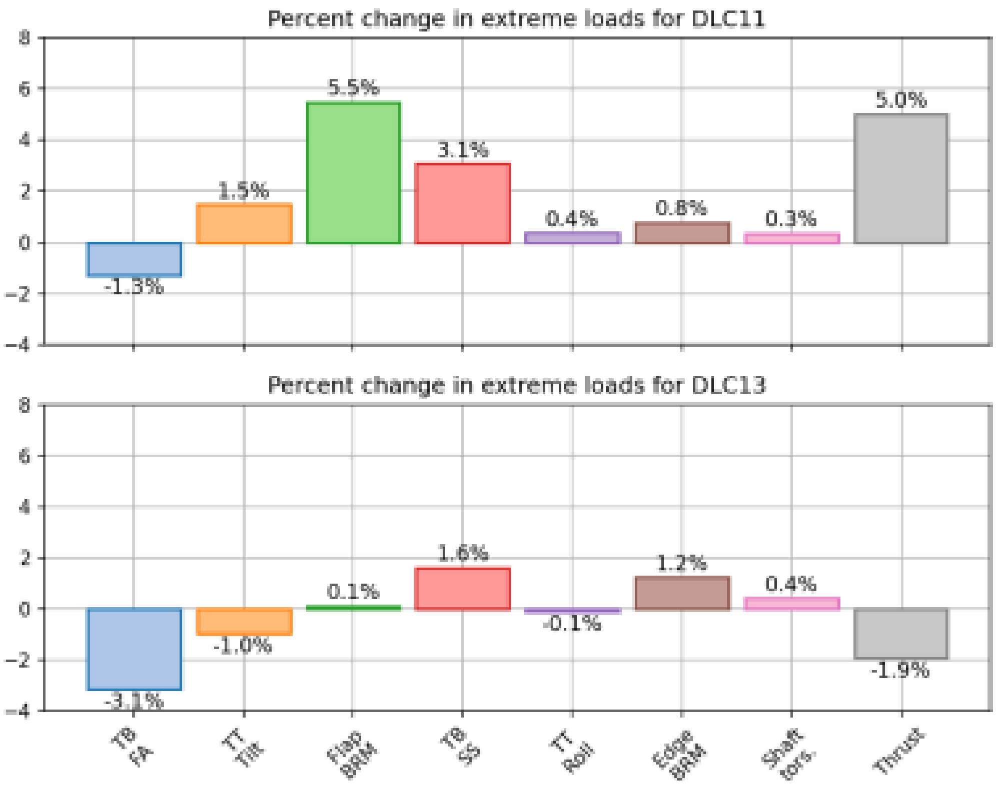

Figure 6: *Ultimate load change when adding VGs conservatively all along the blades*

Also, it should also be mentioned that HAWC2 simulations predicted an increase of AEP of about 0.6%.

Further, a modified XFOIL code [2] was tested against the LM wind tunnel measurements. Figure 7 shows as an example the comparison between the computed and measured polars for the free transition case for standard VGs placed at 40% chord. Table 1 shows the values at maximum Cl and Table 2 Cd at an angle of attack of 0 degrees. It is seen that the modified XFOIL predicts the increased maximum lift fairy well, whereas the predicted increase in drag is too low. This is because XFOIL only computes the effect of the VGs on the airfoil but not the drag from the VGs themselves. Therefore, this code is not suited for optimizing the VG shapes.

Table 1. Maximum Cl comparisons between Xfoil and LM wind tunnel, clean.

Configuration	AoA @ max Cl [deg]	Max Cl [-]	ΔAoA @ max Cl [deg]	ΔMax Cl [%][1)]
XF, no VG	16	1.8061	0	0
LM, no VG	11.163	1.5873	0	0
XF, h = 0.83%c, x = 40%c	17	2.055	1	13.8
LM, h = 0.83%c, x = 40%c	13.451	1.8988	2.288	19.6

[1)] Relative to "no VG"

Table 2. Cd for AoA = 0 deg. comparisons between Xfoil and LM wind tunnel, clean.

Configuration	AoA [deg]	Cd @ 0 deg [-]	ΔCd @ 0 deg [%][1)]
XF, no VG	0	0.00582	0
LM, no VG	-0.032	0.0069	0
XF, h = 0.83%c, x = 40%c	0	0.00642	10.3
LM, h = 0.83%c, x = 40%c	-0.034	0.011218	62.6

[1)] Relative to "no VG"

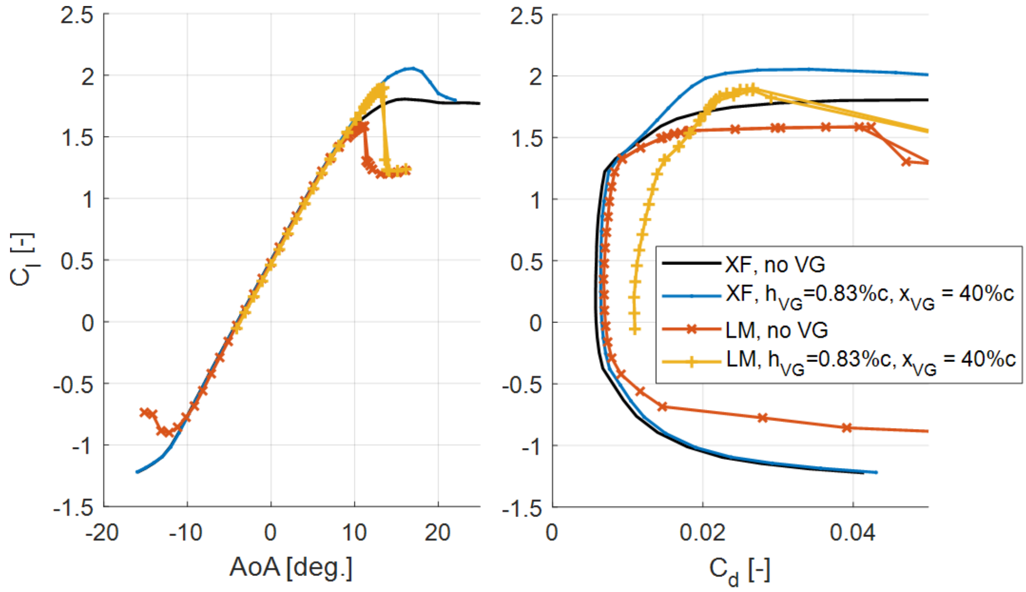

Figure 7: *DU08-W-210 polar, clean. Re = 5 million.*

WP4: Full Scale demonstration

Based on their in-house tools and experience, including 3-D CFD, see Figures 8 and 9, PowerCurve designed the layout for the final full-scale test. Further, PowerCurve delivered a very detailed installation manual that was used to get a quote for the actual mounting. Based on different quotes obtained by companies accepted by Vestas Vento was chosen to do the actual mounting. In the quote was written that Vento could claim a standby charge of 10 hours per day per Technician in case of standby caused by adverse weather. This turned out to be a very expensive surprise since the final bill ended at 28.000 Euro for mounting VGs on two turbines and the quote was only 14.460 Euro. This unexpected extra cost forced the project once again to apply for a re-budget to EUDP and move some man hours into external deliveries and luckily this could be done without compromising the promised work too much. 308 3-D printed Cascade Vortex Generators were finally ordered at Damvig and sent to Vento for the mounting.

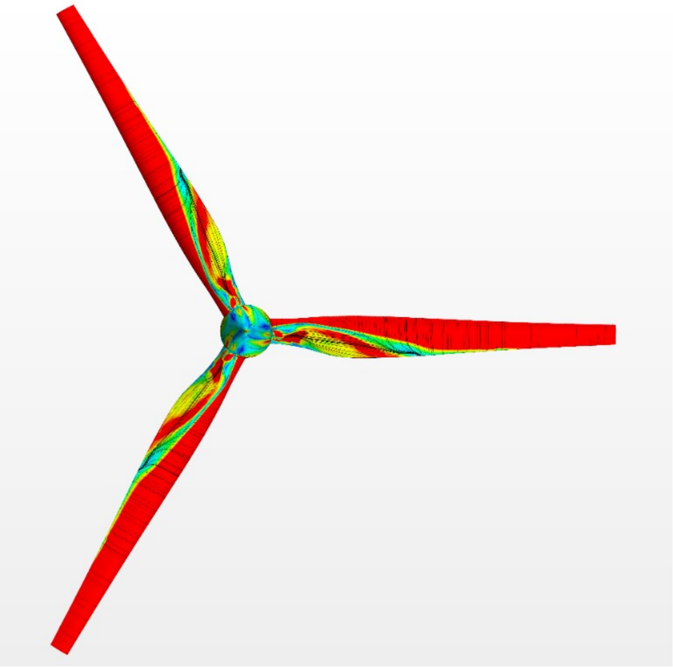

Figure 8: *Full 3-D CFD of wind turbine rotor*. The colours indicate skin friction and red indicates attached flow

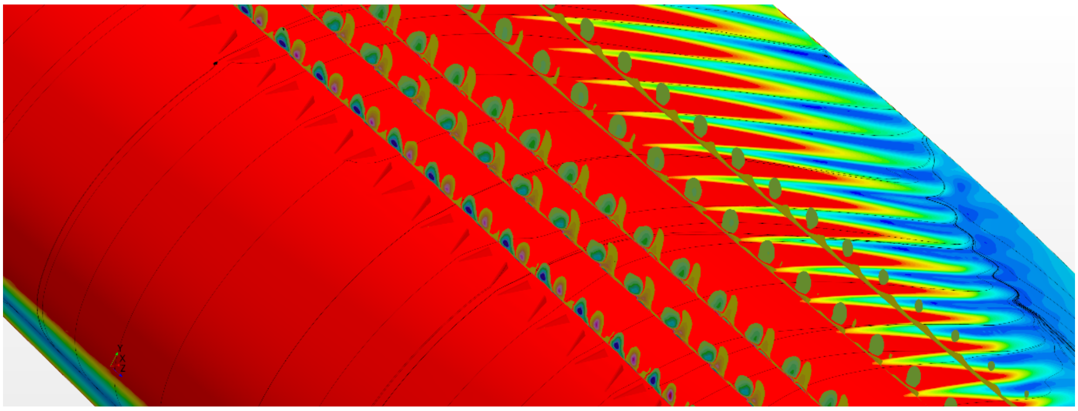

Figure 9: *Zoom in 3-D CFD computation of wind turbine blade including VGs*

Figures 10 and 11 are taken from the installation reports and shows how the VGs were mounted by technicians hanging in ropes from the nacelle

Figure 10: *Installation of the AdvancedVG glued to blade by double adhesive tape and sealed at the edges to prevent water to enter the adhesive area.*

Figure 11: *Installation of the standard PowerCurve SoA VGs to be used for comparison with the AdvancedVGs mounted on the neighbouring WT.*

Due to the weather situation the VGs were mounted in the period between June 8 to August 13 as follows

Nees WT2 (211461) having AdvancedVGs. Blade A: 12/8-13/8, Blade B: 10/8-11/8 and Blade C: 08-09/8
Nees WT3 (211462) having SoA VGs. Blade A: 28/7-30/7, Blade B: 08/06, Blade C: 30/7-31/7

Therefore, only very few SCADA data (a period of 4 month) with VGs are available at the time for writing this report. These are compared to SCADA data from previous years and the very limited data shows an expected increase in AEP between 0.8-1.0% and no significant difference between the two turbines. The measurements will continue after the project until summer 2023 to have more data before a conclusion is drawn. It should be noted that there is a lot of noise and scatter in power measurements and that the potential improvement is a relatively small number and that the conclusion made only from the side-to-side experiment may drown in uncertainty. This was a known risk and has been discussed at project meetings. However, the preliminary increase in AEP fits well the 0.6% estimated by the HAWC2 simulations. However, the aerodynamic improvement of the Cascade VGs compared to the standard VGs in terms of increased lift and the larger lift to drag ratio in the wind tunnel campaigns at LM Wind Power and Risø is very significant and clearly indicates a potential for this new VG geometry.

5. Project results

The objective of the project was obtained, even though the side-to-side experiment does not show a clear result, probably due to the expected improvement being small compared to the uncertainty in power measurements. However, the wind tunnel results clearly show a significant improvement of the Cascade VG compared to SoA.

PowerCurve has made a patent claim and already started to use it in their advertisement as can be seen from their homepage. The commercial target group will mainly be PowerCurve customers.

The geometry and the wind tunnel results are all confidential and has thus not been published yet. However, a paper showing CFD computations of a delta wing VG as the "Ship" geometry described in section 3 was presented at the Torque 2022 conference at TUDelft in the spring 2022 [1]

Utilisation of project results

Various technological results from this project are already being/will be utilised by PowerCurve, namely:

- Wind tunnel and CFD results of the Cascade VG are being used to design and optimise blade-specific configurations (e.g. for Siemens/GE blades) to examine the potential AEP gains in more detail
- CFD techniques developed during the project, especially those used to model a full rotor with VGs are being used to optimise VG layouts in real-world projects
- Knowledge of different 3D printing techniques from producing parts for the wind tunnel campaign will be used to conduct more efficient and cost effective future wind tunnel tests of novel component geometries

The excellent performance results shown by the Cascade VG together with its novelty have led to a number of promising commercial discussions for its deployment with large operators and two different wind turbine OEMs. This has not yet led to direct increases in turnover, employment etc. but PowerCurve are confident of significant commercial rewards when an agreement is made to use the Cascade VG technology. At this time, we believe the most likely commercial path is to license the patented technology.

Based on PowerCurve's market research there are no competitors to the Cascade VG technology – all other VG offerings using a standard triangular fin geometry.

New innovations are often met with barriers in terms of proving that the technology has the desired effect. PowerCurve has a solid reputation of developing technologies to improve the aerodynamics of wind turbines. In recent years our innovations have been acquired and tested by our key partners, who consistently trust in our ability to design and develop successful solutions. PowerCurve will use these relations to overcome potential entry barriers related to the Cascade VGs and to strengthen our business relations. This will contribute to a fast "proof of solution" which will lead to accelerated market penetration.

The Cascade VG will be more efficient at increasing AEP for some blade designs, which will lead to more energy produced from wind turbines due to more VG site roll-outs.

6. Project conclusion and perspective

Early in the project it was decided to focus on only one geometry, the Cascade, and the two wind tunnel campaigns showed a clear improvement compared to SoA. A natural next step is to improve the tools used for designing a good layout of the VGs on a rotating wind turbine blade. There is very likely some more potential in increasing AEP if the use and layout of VGs can be further optimized. A good tool could be using a so called Adjoint CFD solver that are being developed at DTU Wind and Energy Systems. It is expected that such tools will be available within one year.

7. References

[1] Hansen M.O.L and Rogowski R, *Investigation of a delta wing Vortex Generator*, paper#133 and presented at the Torque 2022 conference, TUDelft

[2] De Tavernier D, Baldacchino D, Ferreira C. (2018): An integral boundary layer engineering model for vortex generators implemented in Xfoil, Page 1-16, Wind Energy, https://doi.org/10.1002/we.2204