Slutrapport
Optimization of vortex generators on wind turbine blades
EUDP 64009-0279

Martin O.L.Hansen[1], Clara M.Velte[2], Stig Øye[1], Rolf Hansen[3], Niels N.Sørensen[1]
[1]DTU Wind energy
[2]DTU Mechanics and engineering
[3]LM Wind Power

1. **Introduction**

Vortex generators are small devices that are often glued to the surface of wind turbine blades. Their effect is to improve the aerodynamic efficiency that allows building blades more slender and thus reducing cost and weight. The project focused on finding an optimal placement of existing vortex generators, but also a new geometry is proposed and demonstrated in the wind tunnel at LM Windpower.

Vortex generators (VGs) are small winglets that are commonly applied to wind turbine blades or airplane wings to increase their aerodynamic efficiency, see Fig 1.1. Vortex generators (VGs) have been used in the aeronautical industry since the late 1940's to e.g. control separation on airplane wings.

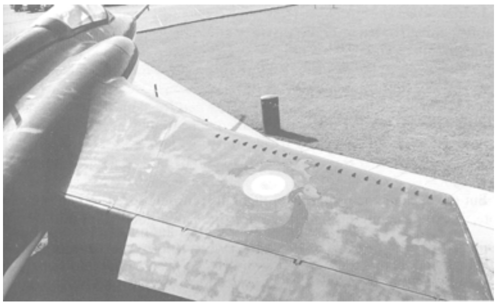


Figure 1.1: VGs on fighter wing.

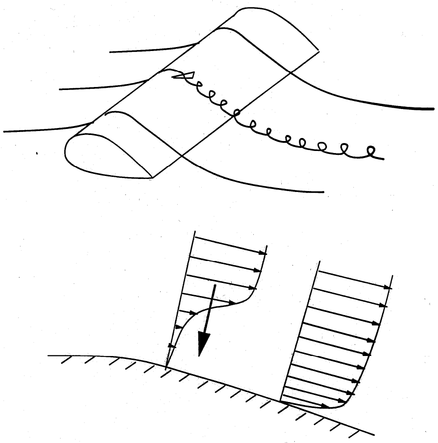


Figure 1.2: Schematic drawing of the flow behind VGs.

VGs were first used to delay separation in diffusers, from where a lot of experience was gained with respect to shape, size etc. The reason for implementing VGs on airplanes is commonly when a prototype does not behave as predicted. The vortex generators can aid in making the flow stay better attached, but with the cost of an increase in drag. Vortex generators are also used to replace more geometrically complex aerodynamic devices such as leading edge slots on STOL (Short Take Of and Landing) airplanes. A wing using vortex generators instead is thus less complicated to build and therefore less expensive. Even though there are similarities between an airplane wing and a wind turbine blade, a wind turbine blade operates for long periods at much higher angles of attack than an airplane wing. For an airplane it can be catastrophic if the flow separates, but on wind turbine blades stall is very common and sometimes even desired.

Vortex generators create longitudinal vortices and more turbulence, see Fig. 1.2, that mix high momentum air from the outer flow down to the boundary layer near the surface, making the flow more resistant to separation in an adverse pressure gradient. The effect of VGs is at high angles of attack to increase lift and in a small range sometimes decrease the drag to enhance the aerodynamic efficiency. For the conditions for which stall does not occur (low angles of attack), however, the price for mounting vortex generators is a small increase in drag, the so called drag penalty.

By applying vortex generators to wind turbines, it is possible to make more slender blades. Hence, the correct application of VGs can yield significant savings in production costs, making wind energy more competitive and thus helping in reducing CO_2 emissions. Further, a more slender blade will be exposed to lower extreme loads at very high wind speeds, where the rotor is either parked or idling that again reduces material cost on other components.

VGs can be mounted so that they give either co-rotating or contra rotating vortices, but this project focus only on contra rotating VGs since they are more effective and the ones used on wind turbine blades. The geometry and the describing of contra rotating VGs are shown in Figure 1.3. Further, where to place the VG cascade along the chord of the blades is also an important parameter.

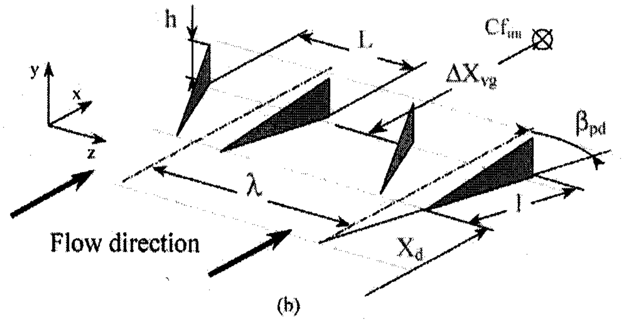


Figure 1.3: Parameters of the VG geometry.

During the project a formal collaboration was made with Laboratorie de Méchanique de Lille (LML) in France. Here some basic experiments were performed in their wind tunnel on three basic VG geometries: a rectangular, a triangular and a cambered rectangular VG, see Fig. 1.4. The flowfield (all three velocity components) were measured at planes 3h, 12h, 25h and 40 or 50h downstream of the different VG geometries, where h is the height of the VG, to see the strength and shape of the created vortex. Besides these measurements some similar experiments were also done in the smaller wind tunnels at DTU.

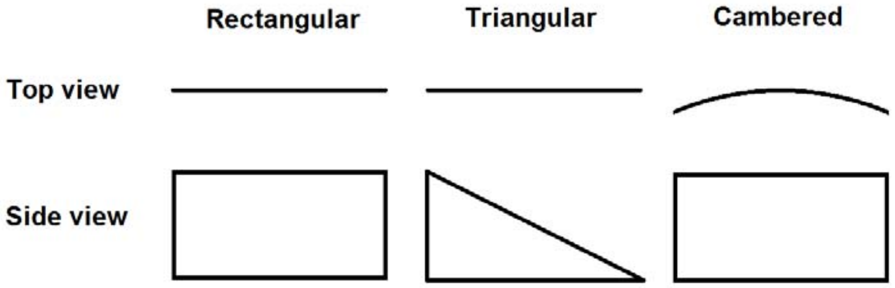


Fig 1.4: Three basic VG geometries measured in the LML wind tunnel in France

Analysing the results from these experiments and some extra measurements done at the laboratory at DTU resulted in some generic analytical models of the topology and stability of the vortices created by the VGs.

The project enabled DTU wind energy to learn how to use Computational Fluid Dynamics to compute the entire flowfield behind a row of VGs on a blade section. The knowledge and experience gained here will be used in future research projects but also directly in consultancy work.

Before this project the geometrical layout of the vortex generators were based on a paper by Godard and Stanislas 2006 [1], where they systematically varied the parameters β_{pd}, λ/h, l/h, L/h shown in Fig 1.3 and measured the increase in skin friction downstream of the VGs on a bump that simulated an adverse pressure gradient on a real airfoil. The optimum found for triangular vanes were $h/\delta=0.37$ (δ being the boundary layer thickness), $l/h=2$, $L/h=2$, $\lambda/h=6$ and $\beta_{pd}=18^o$ and that geometrical configuration was therefore used by LM windpower for a long time. This project, however, enabled LM windpower to do an empirical optimization on an airfoil in their own wind tunnel, and with the result that the optimum geometry found in [1] is not the optimum for a typical wind turbine airfoil.

One of the drawbacks with “conventional” VGs is that they besides the beneficial increase in the maximum lift coefficient also give an increased drag. To reduce this drag it was proposed in this project to design a VG having a different cross section instead of the “conventional” thin plate. It seems that this has a small but measurable effect.

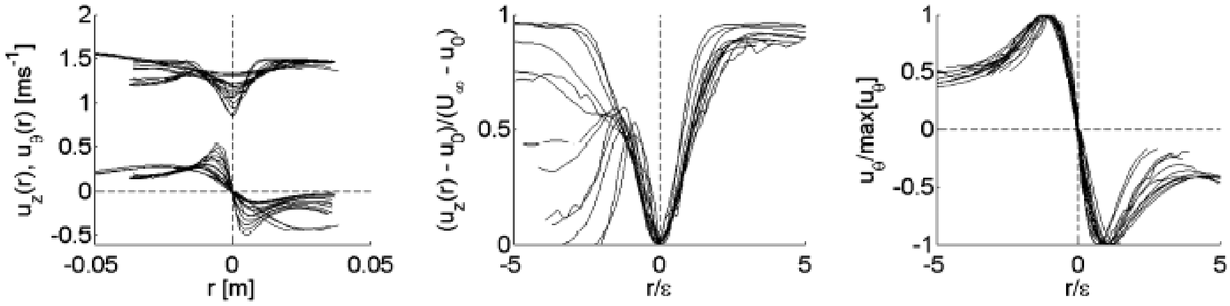
2. Analytical 3-D model

The Bachelor vortex model based on helical symmetry established in Velte et al. [2] is

$$u_\theta = \frac{\Gamma}{2\pi r}\left[1 - \exp\left(-\frac{r^2}{\varepsilon^2}\right)\right]; \quad u_z = u_0 - \frac{\Gamma}{2\pi l}\left[1 - \exp\left(-\frac{r^2}{\varepsilon^2}\right)\right]$$

and was extended by self-similarity analysis in Velte [3].

$$\frac{u_z(r,\theta,z) - u_0(z)}{U_\infty - u_0(z)} = fcn\left(\frac{r}{\varepsilon(\theta,z)}\right)$$



a) b) c)

Figure 2.1: a) is the measured velocity profiles downstream of a VG and b) and c) shows the non-dimensionalized axial and tangential velocity profiles, respectively.

In practice, this means that the flow produced by a VG can be fully described by four parameters (vortex core radius ε, strength Γ, convection velocity u_0 and helical pitch l) - not only in a single downstream position - but the full downstream evolution of the developed wake. If one knows the flow in a single position, one can therefore describe the full flow.

The left part of Figure 2.1 shows a disagreement with the simple vortex model and is caused by the appearance and impact of secondary structures and is investigated in Velte et al. [4] and [5]. Further, the novel type of vortex breakdown from one wake state to another (i.e., no change in flow topology) was studied in Velte et al. [6]. These discoveries pose new challenges in refining the above described model.

3. PIV measurements in the wind tunnel at LM Wind Power

PIV data taken in the wind tunnel at LM Wind Power for a DU-91-W2-250 airfoil done previous to this project was further analysed and documented in Velte and Hansen [7]. A picture of the test section and a sketch of the experimental setup are shown in Fig 3.1 and 3.2, respectively.

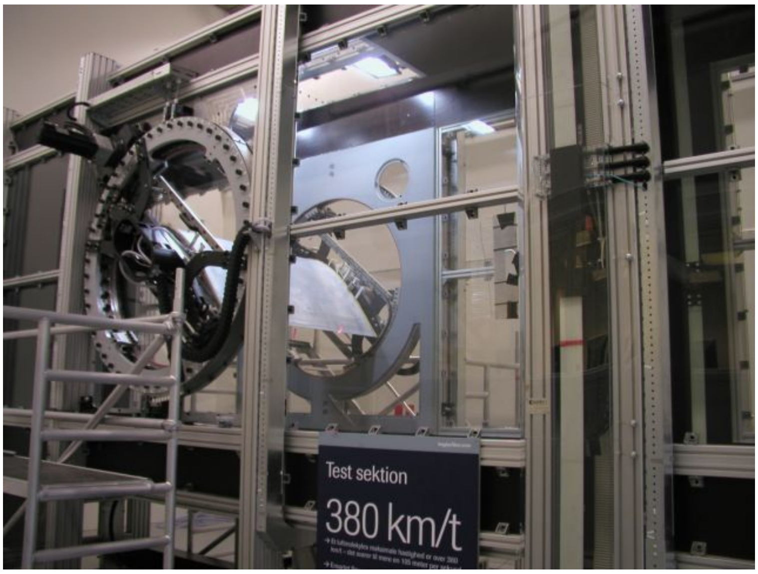


Figure 3.1: Picture of the test section in LM Wind Powers windtunnel

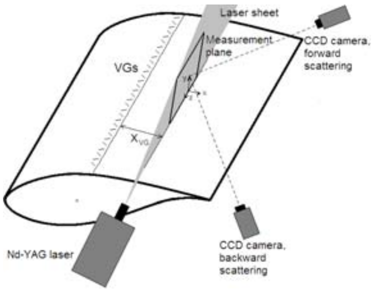


Figure 3.2: Sketch of the PIV setup

The CCD cameras used in the PIV experiment were mounted on the floor besides the wind tunnel and to avoid noise from the vibrations of the test section the wind speed was reduced to 15 m/s corresponding to a Reynolds number of 0.9 million and the angle of attach was fixed at 18^o.

4. CFD

In the project two different types of Computational Fluid Dynamics (CFD) studies were performed to investigate and quantify the effects of vortex generators. One activity was mainly focused on predicting and characterizing the vorticity trailed behind a single vortex generator positions on a flat plate. These computations were used to validate the CFD modelling technique for resolving the flow downstream of the VG, and were compared with the measurements performed in the French LML tunnel [8] and the analytical model Velte [2]. The second part of the CFD studies was aimed at developing an efficient methodology for predicting the effect of a vortex generator on the lift and drag of an airfoil section. CFD computations were performed for airfoil sections with and without vortex generators, and the computations were compared with measurements performed by LM Wind Power in their wind tunnel for the LM-11-02-53 airfoil and measurements from the Stuttgart tunnel. The in-house flow solver EllipSys3D is used in all computations performed in the present project. The code is developed in co-operation between the former Department of Mechanical Engineering at the Technical University of Denmark and The Department of Wind Energy at Risø National Laboratory, see [9-11]. The EllipSys3D code is a multi-block finite volume discretization of the incompressible Reynolds Averaged Navier-Stokes (RANS) equations in general curvilinear coordinates. The code uses a collocated variable arrangement, and Rhie/Chow interpolation [12] is used to avoid odd/even pressure decoupling. As the code solves the incompressible flow equations, no equation of state exists for the pressure, and in the present work the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm of Patankar and Spalding [13] is used to enforce the pressure/velocity coupling. The EllipSys3D code is parallelized with the Message-Passing Interface (MPI) for executions on distributed memory machines, using a non-overlapping domain decomposition technique.

4.1 Vortex Generators on Flat Plates

Both square and delta shaped VG's were investigated in connection with the flat plate setup. Here an example of a setup with delta shaped VG's are shown. The VG's are resolved with an O-O-topology with 384 cells around the VG, 64 cells in the direction normal to the tunnel wall, and a single 64 × 64 tip cap block. In the direction normal to the VG over a distance of 0.1 × height of the VG 64 cells are used with a first cell height of 1×10^{-5} meter. A series of blocks are used to merge the VG grid with the surrounding 'Cartesian' grid. The total grid consists of 72 blocks of 64^3 cells or a total of 19 million cells. The cross-flow boundary conditions are specified as periodic, inlet/Dirichlet conditions are used at the upstream and lid boundaries, outlet/fully developed conditions are specified at the downstream boundary. An overview of the block topology for this gris is hown in Figure 4.1.

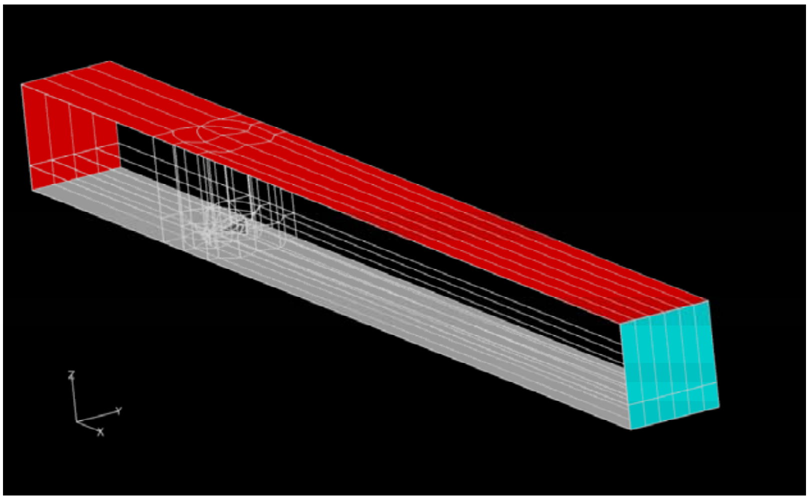


Figure 4.1: Overview of block topology for the single VG on a flat surface

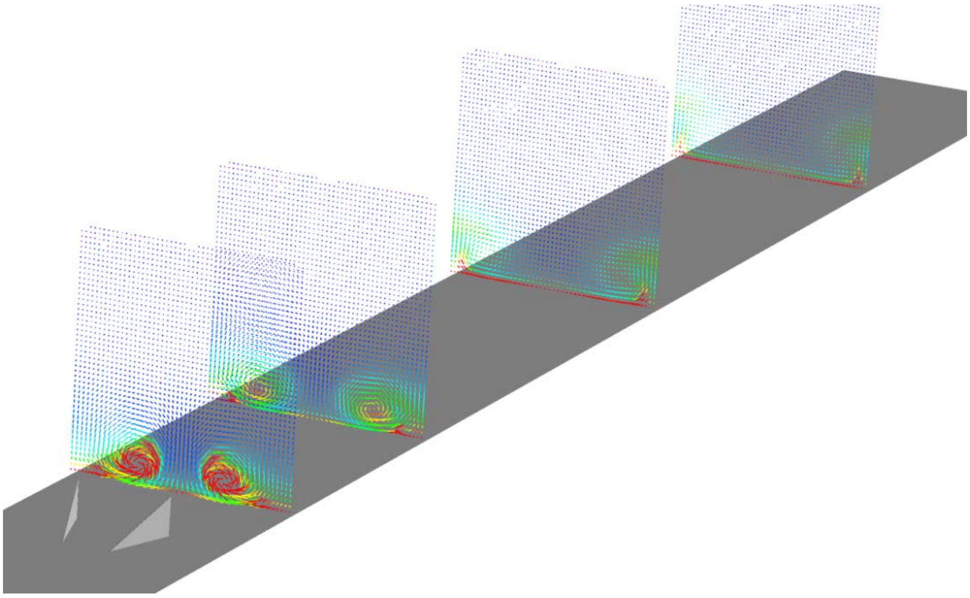


Figure 4.2: Computed vortices behind a pair of contrarotating VGs

More details about the VG simulations on flat plates can be found in Fernandez et. Al. [14] where the results of the simulations are compared with measurements and an analytical model by Velte [**Error! Bookmark not defined.**]

4.2 Vortex Generators on an airfoil

Having verified that the CFD methodology was capable of capturing the wake structure behind a single VG, the next step was to investigate if the method was also capable of capturing the effect of VGs on the lift and drag of an airfoil section. The vortex generator configurations investigated in the present work are all counter rotating configurations as also seen in **Error! Reference source not found.** In order to limit the computational requirements, only half of the full VG pair consisting of two surface mounted triangular plates was simulated, exploiting the geometrical symmetry of a VG unit, see Figure 4.3. The parameters characterizing the VG configuration, is the height, the aspect ratio of the delta wings, the angles of the triangular wings with the oncoming flow, and the inter and intra spacing of the VG units.

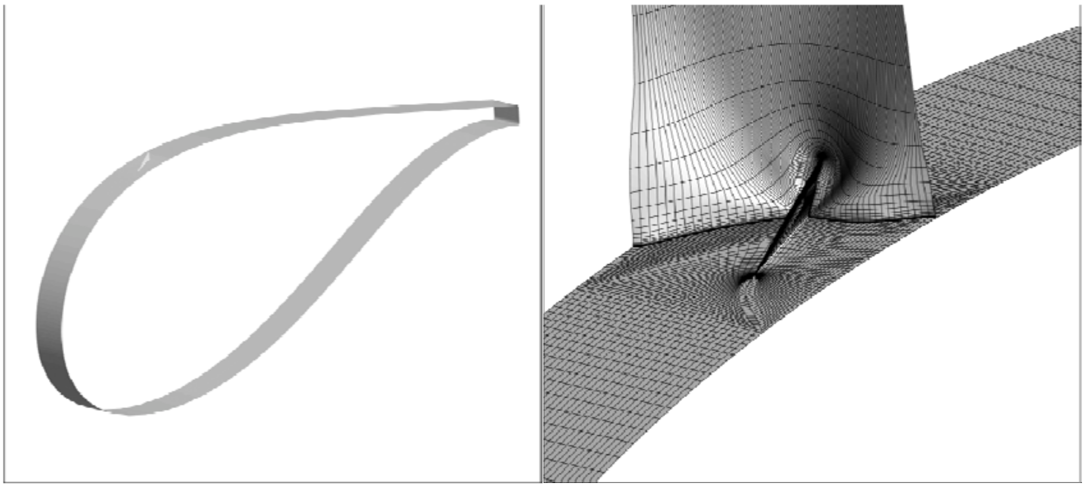


Figure 4.3: Airfoil section with a VG pair approximately at x/C=0.2. The left picture shows the full section and the right picture shows a zoom on the VG.

The present methodology was used to simulate several different airfoil setups equipped with VGs, two FFA airfoils FFA-W3-301 and FFA-W3-360, and the 53% thick LM-11-02-53 airfoil. The methodology was used both to investigate the effect on the lift and drag from the chord-wise position, the span-wise inter and intra spacing of the VG units and angle of the VG towards the oncoming flow.

To illustrate the capability of the present methodology, the method has been applied to the FFA-W3-360 airfoil equipped with a VG at x/C=0.15 as shown in Figure 4.4, where a comparison is done between a clean airfoil and the same airfoil equipped with VGs. It is clearly illustrated that the methodology is capable of predicting qualitatively and also to a good degree quantitatively the effect of the vortex generator on the lift. Especially the delay of the stall angle and the more abrupt stall is very well predicted by the method.

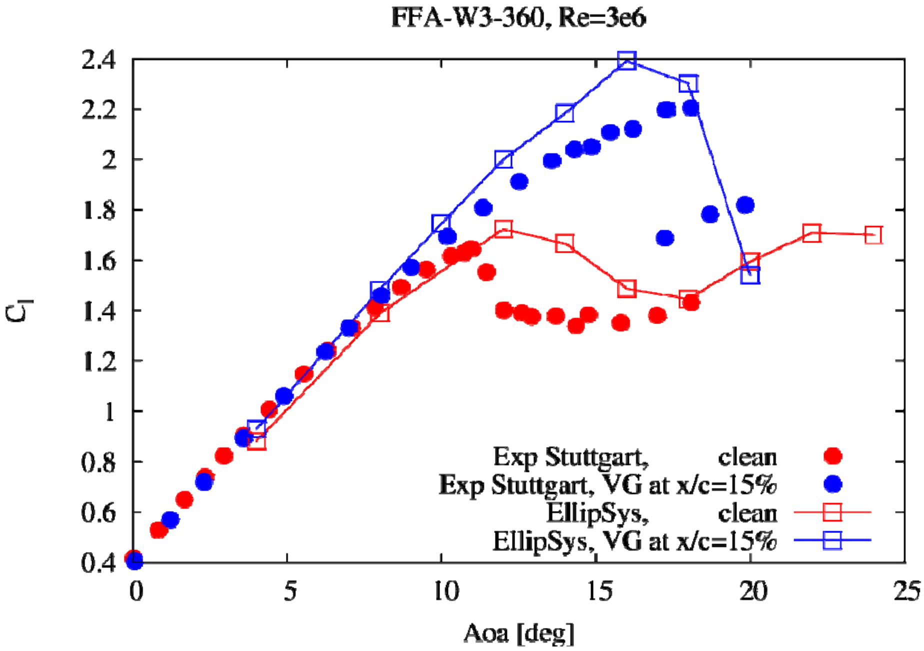


Figure 4.4: Comparison between experimentally and computed lift for the FFA-W3-360 airfoil with and without VGs at x/C=0.15

For the methodology to be working the computational grid needs to be sufficiently fine to allow the computation to capture the trailed vortex behind the vortex generator along the full downstream extent of the airfoil and failing to do this the method will not predict the correct effect of the VG. An easy way to assure sufficient resolution is standard grid refinement studies. In Figure 4.5, it is illustrated how the present computations are capable of resolving the vortex all the way to the trailing edge of the airfoil.

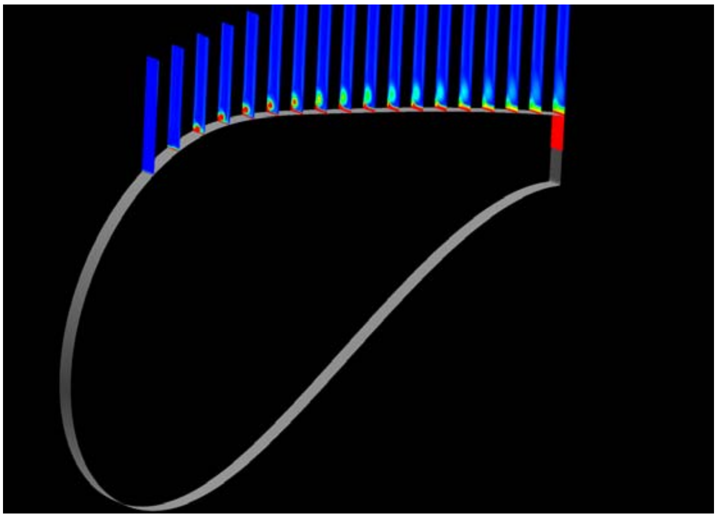


Figure 4.5: A computation of the LM-11-02-53 airfoil clearly showing the presence of the generated vortex all the way to the trailng edge

It is concluded that a methodology capable of predicting the qualitative and to a good degree also the quantitative effect of VG on airfoil performance has been developed. The method is capable of predicting the delay in stall angle and the increase of the maximum lift coefficient $C_{l,max}$. Additionally, the method also predicts the more abrupt stalling behaviour of airfoils equipped with VG's.

5. Empirical optimization

The project allowed LM Wind Power to perform a series of parametric experiments studying systematically the influence of the various geometric parameters for their standard triangular VG geometry. This study resulted in an improved configuration that has replaced the findings from what was common practise at the beginning of the project [1].

6. Demonstration experiment

Finally a new VG geometry was proposed and tested at LM Wind Power and the conclusion was that an even better performance can be achieved. It is presently investigated whether this geometry should be patented and a description of the actual geometry and the results from the demonstration tests are therefore not included in this report.

7. Conclusions

New detailed velocity fields behind VGs have been measured using advanced optical methods. These provide a better insight into the physics behind the flow past VGs, they can be used to validate CFD computations and they have been used to derive a simple analytical model for the generated vortex.

The project has provided guidelines and knowledge of how to model the flow using CFD methods. In the beginning of the project it was considered a risk that this would not be possible since VGs are placed deep into the boundary where viscous effects are high and where flow structures such as a vortex may easily be dissipated by numerical viscosity. But actually very good results were obtained for several configurations.

The project has allowed LM Wind Power to perform systematic parameter studies enabling them to place VGs more optimal as was done at the beginning of the project.

Finally, a new VG geometry has been proposed and tested in the wind tunnel at LM wind power. The results give a small but consistent improvement compared to the conventional triangular plates used as standard and it is investigated if it worth patenting.

References

[1] Godard G., Stanislas M., "Control of a decelerated boundary layer. Part 1:Optimization of passive vortex generators", Aerospace Science and Technology, vol. 10, pp. 181-191, 2006

[2] Clara M. Velte, Martin O. L. Hansen, Valery L. Okulov, ``Helical structure of longitudinal vortices embedded in turbulent wall-bounded flow'', Journal of Fluid Mechanics, vol. 619, pp. 167-177, 2009.

[3] Clara M. Velte, ``A Vortex Generator Flow Model Based on Self-Similarity'', AIAA J., vol. 51, No. 2, pp. 526 -- 529, 2013.

[4] Clara M. Velte, Valery L. Okulov, Igor V. Naumov, ``Regimes of flow past a vortex generator'',
Technical Physics Letters, vol. 38, no. 4, pp. 379 -- 382, 2012.

[5] Clara M. Velte, Valery L. Okulov, Martin O. L. Hansen, ``Development of multiple vortex structures in the wake of a vortex generator'', under preparation for AIAA Journal 2014.

[6] Clara M. Velte, Valery L. Okulov, Martin O. L. Hansen, ``Alteration of helical vortex core without change in flow topology'', Physics of Fluids, vol. 23, 051707, 2011.

[7] Clara M. Velte, Martin O.L. Hansen, ”SPIV study of Passive Flow Control on a WT Airfoil Near Stall'', Wind Energy, vol. 16, pp. 775-785, 2013

[8] Foucaut, JM, Coudert, S, Braud, C & Velte, CM 2012, 'Large field SPIV with separated sheets in a spanwise plane of a turbulent boundary layer with vortex generators'. in Proceedings of the 16th International Symposium on Applications of Laser Techniques to Fluid Mechanics.

[9] Michelsen, J.A.. Basis3D - a Platform for Development of Multiblock PDE Solvers. Technical Report AFM 92-05, Technical University of Denmark, 1992.

[10] Michelsen, J.A.. Basis3D - a Platform for Development of Multiblock PDE Solvers. Technical Report AFM 92-05, Technical University of Denmark, 1992.

[11] Sørensen, N.N.. General Purpose Flow Solver Applied to Flow over Hills. Risø-R-827-(EN), Risø National Laboratory, Roskilde, Denmark, June 1995.

[12] C. M. Rhie. A numerical study of the °ow past an isolated airfoil with separation . PhD thesis, Univ. of Illinois, Urbana-Champaign, 1981.

[13] S.V Patankar, D.B Spalding. A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows International Journal of Heat and Mass Transfer, Volume 15, Issue 10, October 1972, Pages 1787–1806.

[14] Fernandez, U, Réthoré, P-E, Sørensen, NN, Velte, CM, Zahle, F & Egusquiza, E 2012, 'Comparison of four different models of vortex generators'. in Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition. European Wind Energy Association (EWEA).