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Optimization of Profile Polars for Wind Turbine Rotor Blades with the Use of Leading-Edge Vortex Generators

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Abstract

The influence of sinusoidal leading edge tubercle- and Leading Edge Vortex Generator (LEVoG) technology on the performance of wind turbine airfoils have been investigated in the UniBwM wind tunnel for the Reynolds number $Re = 8.0 \times 10^5$. Infra-red thermography and oil flow visualization were implemented for the flow visualization and the lift- and drag measurements obtained with the use of an above-tunnel force scale and a wake rake. At lower incidences the tubercles and LEVoGs are located close to the stagnation point and the suction side flow remains unaffected. At higher incidences longitudinal vortices are induced which impact the suction side flow, lowering the lift production. With a parameter study the influence of the LEVoG parameters were analysed for the ability to limit the lift production beyond the operation point. The tubercle amplitude and leading edge radius have the largest influence on the performance with a larger peak radius preventing the formation of laminar separation bubbles and maintaining a higher lift production in comparison. The LEVoG height to boundary layer thickness as well as the LEVoG's distance to the leading edge was found to have the largest influence on the performance and an optimum ratio for the distance between LEVoGs is observed. An optimum LEVoG configuration was defined for the tested case.

1 Introduction

Wind turbine blades experience strong alternating loads over the length of the rotor blade which severely limit the service lifespan of the wind power plant. Due to wind gusts, which prevail in a turbulent atmosphere, the angle of attack over the rotor blades can be increased. This in turn results in an increased local lift and causes the occurrence of an alternating load over the wind turbine blade. In order to improve the lifespan and efficiency of the wind power plant, it is of interest to limit the occurrence of alternating loads on the rotor blades by limiting the lift production beyond the operation point. The use of sinusoidal leading edge tubercles and DLR Leading Edge Vortex Generator (LEVoG) technology have been identified as possible solutions.

The tubercles on the humpback whale's flippers were first identified by Bushnell and Moore (1991) for it's improved stall performance. Fish and Battle (1995) concluded that the leading edge tubercles act as large vortex generators to generate vortices along the length of the fin in order to maintain lift and delay stall at higher angles of attack. Subsequent experimental and numerical studies have shown that the tubercles aid in keeping the flow attached to the surface in order to postpone stall, while also reducing the lift production due to the formation of stream-wise vortices. Although tubercles offer a promising solution, it is more complex to manufacture and retrofit to existing wind turbines, increasing the costs and reducing the overall effectiveness of implementation. The use of a smaller device with a similar effect as the tubercles, but which is more suitable for retrofitting, is therefore of high interest.

Geissler et al. (2005) first developed the Leading Edge Vortex Generator (LEVoG) as a passive flow control device by means of miniature, low aspect ratio vortex generators added to the profile leading edge. Further wind tunnel experiments with the rotary aircraft profile OA209 were carried out by Mai et al. (2008)

and an optimum configuration identified for the improvement of dynamic stall conditions. It was concluded that, due to the LEVoGs location in or near the stagnation point, the flow remained unaffected at lower angles of attack, only forming small longitudinal vortices over the upper airfoil surface at higher angles of attack. Heine et al. (2010) investigated the wake of a cylinder with the implementation of LEVoGs with an aspect ratio of 0.09. A pair of counter rotating vortices were observed, which induced an upward facing velocity resulting in an increased wake height. A LEVoG height slightly larger than the boundary layer was thus suggested. However, in the paper of Heine et al. (2013) for the implementation of LEVoGs on the OA209 profile, it was observed that a larger height and larger spacing were more successful in delaying stall. The existing investigations into LEVoGs, as well as the optimum LEVoG configurations defined in previous research, mainly focused on the improvement of dynamic stall conditions. Therefore, further research is needed to optimise LEVoGs for the use in wind turbine applications, in which a limited lift production after the operation point is desired in order to reduce undesirable alternating loads on the rotor blades.

The aim of the present paper was the investigation of the effect of the tubercles and LEVoGs on laminar, wind turbine airfoils with the use of a parameter study and flow visualization. Measurements with a large range parameter study of the LEVoGs resulted in a database of the aerodynamic performance implemented to optimize the profile polars for the Reynolds number $Re = 8.0 \times 10^5$.

2 Experimental Setup

The low-speed wind tunnel at the Universität der Bundeswehr München (UniBwM) was implemented for the experimental investigation. The wind tunnel design is that of a closed circuit, open-jet test section with a maximum flow velocity of $U_\infty = 40.0\,\mathrm{m\,s^{-1}}$, turbulence level of appr. $Tu = 0.35\,\%$ (cf. Eulitz (2014)) and an average Reynolds number $Re = 8.05 \times 10^5$ for the model chord. Two laminar, wind turbine airfoils TEG4418 and TEG2618 were used as the reference clean wing profiles, characterized in Tab. 1. Models with a chord length of $c = 0.35\,\mathrm{m}$ and model span of 0.8 m were constructed from WB1222 Polyurethane block material and fitted with circular end-plates, radius $r = 2{\cdot}c$, to preserve a 2D flow.

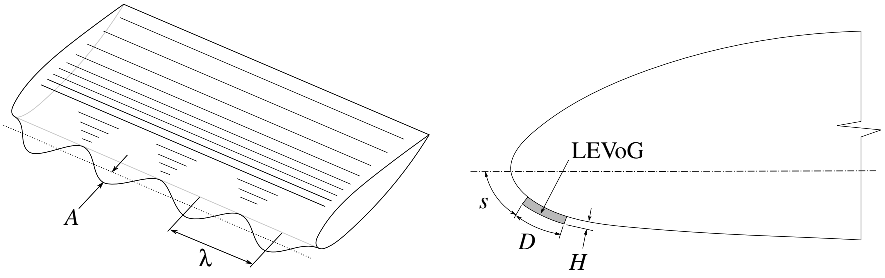
Flow visualization was obtained with the use of oil flow visualization as well as implementing an Infrared thermography (IRT) camera. Lift forces were measured with an overhead force scale and the drag measured with the use of a wake rake. The wake rake consisted of 80 total- and 7 static pressure tubes with a rake height of $y/c = 1.43$ and mounted $x/c = 0.6$ downstream of the model trailing edge in the center plane of the test section. Two MicroDAQ-64DTC-Q systems from Chell Instruments Ltd with the corresponding MicroDAQ software were implemented for the data acquisition. The static and total pressure was calculated as a mean value of 500 consecutive measurements with a sample rate of $f = 0.01\,\mathrm{Hz}$ and implemented for the calculation of the profile drag by analysing the momentum loss in the profile wake, as constructed and validated by Terreblanche (2017).

2.1 Design of tubercles

The tubercle models were formed by adding sinusoidal tubercles at the leading edge of the clean wing airfoils (see Fig. 1(a)). The shape of the tubercles is controlled by the amplitude A, wave length λ and the form of the tubercle peaks named V, D and Disc. The form V and D indicate the difference in the resulting leading edge radius of the tubercle peaks with the D form implementing a larger radius at the peak and creating a noticeable valley at the trough. The Disc configuration created a plateau at the trough without changing the amplitude or wavelength of the tubercles. Detailed information on the parameter variation is given in Tab. 2.

Table 1: Basic design information of the reference airfoils.

Airfoil	Max thickness t [%·c]	Point of max thickness $x_{t,max}$ [%·c]	Leading edge radius r_{LE} [%·c]	Cross-sectional area A_z [%·c]
TEG4418	18.00	40.9	1.42	11.38
TEG2618	18.37	35.1	1.96	11.51



(a) Drawing of an airfoil with tubercles (b) Side view of the LEVoG positioning

Figure 1: Positioning and parameters of the sinusoidal tubercles and circular LEVoGs, with the amplitude A, wavelength λ, diameter D, height H and LEVoG distance from the leading edge s. Adapted from Mai et al. (2008) and Heine et al. (2009).

Table 2: Tubercle configurations and adopted terminology.

Airfoil	Label	Wavelength λ [%$\cdot c$]	Amplitude A [%$\cdot c$]	Form	Chord length c_{eff} [m]
TEG2618	W38A5V	38	5	V	0.359
TEG4418	W38A5V	38	5	V	0.359
	W38A7,5V	38	7.5	V	0.363
	W38A7,5D	38	7.5	D	0.363
	W38A7,5Disc	38	7.5	Disc	0.363
	W38A10V	38	10	V	0.368
	W19A7V	19	7	V	0.362

2.2 Design and application of Leading Edge Vortex Generators

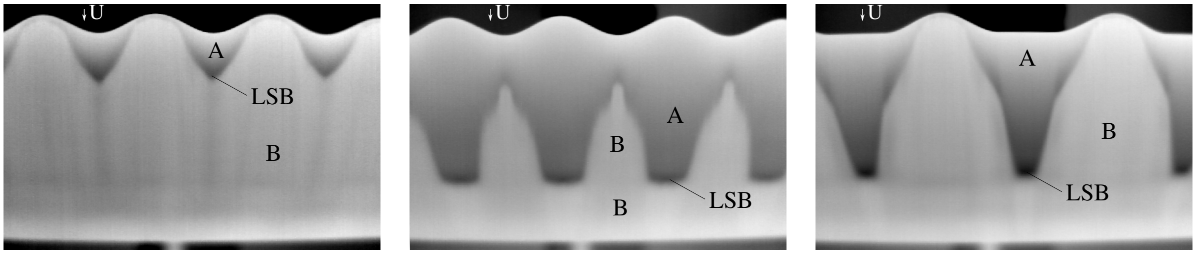
The presently tested LEVoGs were shaped as flat cylinders, cut from foam rubber with a thin layer of adhesive tape applied to the bottom side in order to be glued onto the model surface. The LEVoGs were applied to the model leading edge over the entire span. The LEVoG parameters for the diameter D, height H, span-wise spacing S and distance from the leading edge s were varied systematically in order to identify an optimum configuration for the tested case (see Fig. 1(b)). The total ranges tested include: A LEVoG diameter of $1.14\,\%\cdot c \leq D \leq 2.86\,\%\cdot c$, height of $0.14\,\%\cdot c \leq H \leq 0.66\,\%\cdot c$, span-wise spacing between the LEVoGs centre-to-centre of $4.29\,\%\cdot c \leq S \leq 14.29\,\%\cdot c$ and distance from the leading edge $0\,\%\cdot c \leq s \leq 2.86\,\%\cdot c$.

3 Results

3.1 Tubercle technology

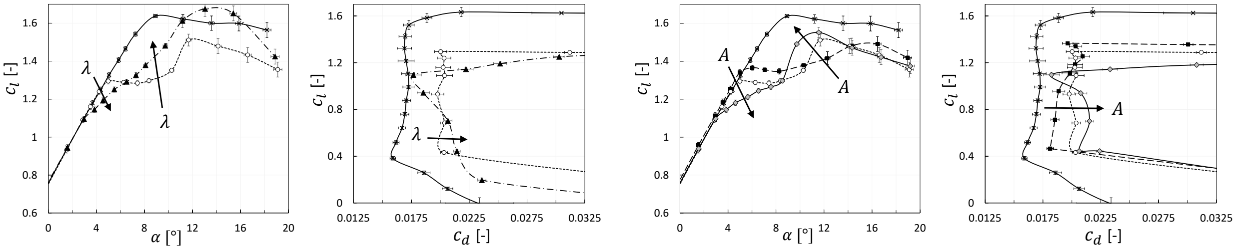
It is observed that stream-wise vortices are formed either side of the tubercles which accelerate the flow in the trough region and result in delayed transition to a turbulent flow. For tubercles with a small leading edge radius, a laminar separation bubble forms on the tubercle peak. This results in a turbulent flow behind the peak and a laminar flow to be maintained for higher angles of attack behind the trough (see Fig. 2(a)). In the case of a larger leading edge radius and deeper valley at the trough, a greater flow attachment is observed behind the peaks (see Fig. 2(b)). It is concluded that the larger peak radius prevents the formation of a laminar separation bubble at lower incidences, therefore resulting in a larger region of laminar flow and a higher lift production (see Fig. 3(c)).

The findings indicate that the wavelength influences the activation angle, at which the lift production is affected, as vortices in closer proximity lead to the earlier onset of instability behind the troughs. The amplitude is observed to have a larger influence on the performance however, with a larger amplitude resulting in a higher drag increase and a decreased activation angle (see Fig. 3(b)). The activation angle could however only be varied between 3° and 4.8° for the tested parameter range. By displacing the tubercles, creating a plateau at the trough with the Disc-form (see Fig. 2(c)), it is observed that the neighbouring counter-rotating vortices only interact and merge at higher angles of attack. This results in a larger region of laminar flow

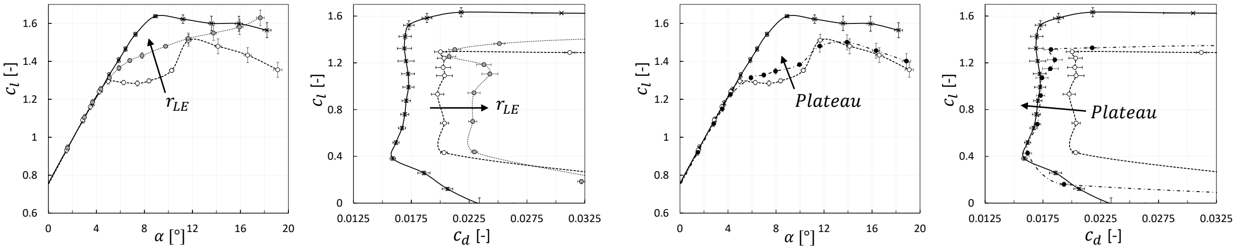


(a) TEG4418-W38A7.5V at α = 6.2° (b) TEG4418-W38A7.5D at α = 5.9° (c) TEG4418-W38A7.5Disc at α = 6.1°

Figure 2: IRT flow visualization for the tubercle V-, D- and Disc- configurations for $Re_{avg} = 8.06 \times 10^5$. Flow regime indicated for A) laminar flow, B) turbulent flow and LSB) laminar separation bubble.



(a) Varying wavelength λ (b) Varying amplitude A



(c) Varying leading edge radius r_{LE} (d) Increased plateau of disc form

Figure 3: Comparison of profile polars for the TEG4418 airfoil clean wing case (solid line) compared to wing with tubercles for varying tubercle amplitude A, wavelength λ, peak leading edge radius r_{LE} and increased plateau distance for $Re_{avg} = 8.06 \times 10^5$.

to be maintained behind the troughs and a smaller separated region at the trailing edge. The Disc-form thus results in a decreased lift production and minimal drag increase (see Fig. 3(d)). It should be noted that in previous research, as observed by Johari et al. (2007) and Hansen et al. (2010), it was found that the tubercle effectiveness reduced with a decrease in the Reynolds number, as this resulted in an increased drag. It can therefore be expected that the observed drag penalty for the current application should be reduced for higher Reynolds numbers.

3.2 Leading Edge Vortex Generator technology

With the parameter study, the LEVoG parameters are varied and the effects on the flow analysed. The flow experiences an acceleration between the LEVoGs resulting in delayed transition. As the LEVoG wake size increases and interacts with neighbouring wakes downstream, the point of transition slowly creeps upstream with increasing angles of attack. It is observed that the implementation of LEVoGs maintains an attached flow on the front 19 % of the wing at an angle of attack $\alpha \approx 14°$, with the vortex streets behind the LEVoGs delaying separation up to appr. 58 %. This results in a lowered but maintained lift production with delayed separation. Parameter ranges which produces the best results for the TEG4418 airfoil at a Reynolds number $Re_{avg} = 8.04 \times 10^5$ are identified for the LEVoG model configuration, relative to the airfoil chord length c,

for a diameter $D = 1.71\,\%{\cdot}c$, height $H = 0.43\,\%{\cdot}c$, distance from the leading edge $s = 1.14\,\%{\cdot}c$ and span-wise spacing $S = 5.71\,\%{\cdot}c$ (see Fig. 4).
It is observed that the addition of the LEVoGs do not affect the lift performance before the activation angle. The addition of the LEVoGs result in a higher overall drag coefficient but experiences a decrease in drag when located in or near the stagnation point. For the optimum LEVoG configurations the drag is observed to be lower than the clean airfoil case for a narrow incidence range pre-LEVoG activation. This effect is however attributed to the larger influence of the laminar separation bubble at lower Reynolds numbers. Furthermore, it is concluded that due to the difference in the position of the stagnation point for different airfoils, the LEVoG activation angle is affected and is attributed to the local boundary layer thickness δ. Due to the large influence of the LEVoG parameters, the activation angle could be varied between 3° and 7° with a 7.3 % reduction of the maximum lift. Of the LEVoG parameters, the LEVoG distance from the leading edge s as well as height H are found to have the largest influence on the aerodynamic performance. Both influence the ratio of LEVoG height to boundary layer thickness H/δ (see Fig. 5(a)) with the optimum ratio found for the range $2 \leq H/\delta \leq 5$. The boundary layer thickness δ was numerically calculated using XFOIL for the TEG4418 clean wing airfoil with a Reynolds number $Re = 8.05 \times 10^5$, Mach number $Ma = 0.11$ and critical amplification factor used by XFOIL of $N_{crit} = 8$. An optimum ratio of the LEVoG span-wise spacing to diameter S/D is also observed as a reduced effective spacing between the LEVoGs S_{eff}, affected by both the span-wise spacing S and diameter D, results in a significantly increased drag (see Fig. 5(b)). The optimum ratio is identified for the range $2.8 \leq S/D \leq 5.0$.

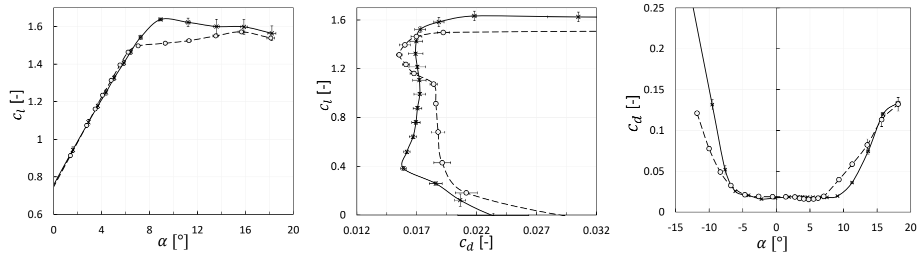
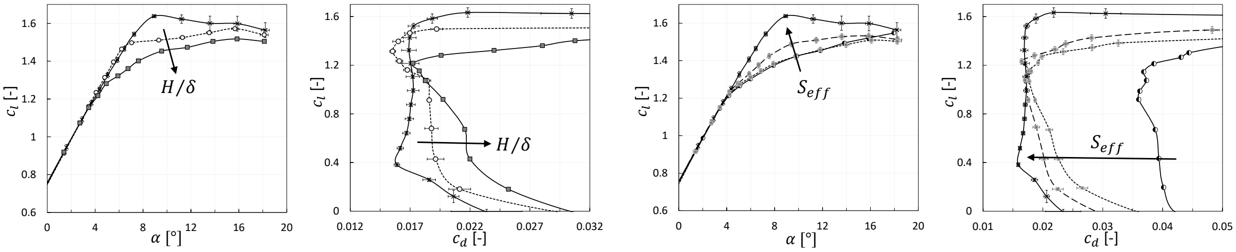


Figure 4: Measured lift, lift-drag and drag polar for $Re_{avg} = 8.04 \times 10^5$ of the TEG4418 airfoil clean wing case (solid line) compared to wing with LEVoG configuration $D = 1.71\,\%{\cdot}c$, $H = 0.43\,\%{\cdot}c$, $s = 1.14\,\%{\cdot}c$ and $S = 5.71\,\%{\cdot}c$ (dashed line).



(a) Varying hight to boundary layer thickness H/δ

(b) Varying effective spacing S_{eff}

Figure 5: Comparison of profile polars for the TEG4418 airfoil clean wing case (solid line) with varying LEVoG hight to boundary layer thickness H/δ and varying effective spacing between LEVoGs S_{eff} for $Re_{avg} = 8.04 \times 10^5$.

4 Conclusion

Experimental results are presented for the implementation of sinusoidal leading-edge tubercles and leading edge vortex generators (LEVoGs) on laminar, wind turbine airfoils TEG4418 and TEG2618 at a Reynolds number $Re = 8.0 \times 10^5$. The measured lift and drag polars, infra-red thermography and oil flow visualization are used for investigation of the flow and the parameter analysis. Implementing an increased plateau between tubercles was found to reduce the lift with a minimal drag penalty. Variation of the tubercle parameters however do not allow significant adjustment of the activation angle, at which the lift is first affected. The implementation of LEVoGs does offer a larger variation of the activation angle. A flatter lift curve after activation is however only possible with a higher activation angle, which in turn only offers a small reduction of the maximum lift. The ratio of the LEVoG height to boundary layer thickness is found to be a driving factor, with the optimum ratio for the current application found to lie between 2 and 5. An optimum ratio for the spacing to diameter is also identified and defined for the range 2.8 to 5.

The results from the analysis of the tubercle and LEVoG parameter variation are consistent with that observed in previous research. The findings suggest that both tubercles and LEVoGs can be implemented to lower the lift production beyond the operation point for use in wind power plants. Additionally, this research offers a better understanding of the effect of the LEVoG parameters on the resulting aerodynamic performance. Future investigations at higher Reynolds numbers are necessary to determine whether, and to what degree the effect of the LEVoGs changes with an increased Reynolds number.

Acknowledgements

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