The Effect of Vortex Generators on the Flow around a Circular Cylinder

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Abstract The effect of circular low-profile vortex generators for rotorcraft application has been investigated on a circular cylinder at a high Reynolds number. These so called Leading Edge Vortex Generators (LEVoGs) have shown significant reductions on the impact of dynamic stall on a pitching helicopter airfoil. However, the principle of operation of such devices remained unclear. In order to understand the aerodynamic phenomena, a wide range of experimental techniques such as oil flow visualization, infrared thermography, surface pressure measurements and stereo particle image velocimetry were employed. In addition, several post-processing approaches such as the proper orthogonal decomposition method were selected. The passive devices were found to significantly alter the flow around the cylinder. Depending on the azimuth angle of the vortex generators, the flow conditions could be classified into three categories, each with characteristic features. Similar to previous experiments on a helicopter rotor blade section, bundling of vortex generator wakes could be found under certain conditions. The vortex generators reduced the periodic Reynolds stress components $v'^2/U_\infty^2$ and $u'^v'/U_\infty^2$ for all cases. For the cases where bundling was present, the size and peak values of the periodic $u'^2/U_\infty^2$ component was increased significantly compared to the clean case. This means that the vortex generators almost only influence the periodic motion of the flow under these conditions. Even though the principle of operation couldn't be entirely cleared, the present study sheds some light onto the various mechanisms in the flow around such devices.

1. Introduction

The flight speed of helicopters is limited by two main aerodynamic factors: transonic flow at the tip of the advancing blade and stall at the retreating blade. While at the advancing blade rotational and forward speeds add up, the retreating blade faces low velocities and partially even reverse flow. In order to maintain constant lift over the entire rotor disc, high angles of attack are necessary for the retreating blade. The rotor blade therefore has to perform a periodic pitching motion. At a certain forward speed, stall occurs at some part of the retreating blade. This phenomenon, referred to as dynamic stall, leads to a series of complicated aerodynamic mechanisms and has been studied by numerous researchers. It induces an abrupt decay and fluctuation of the aerodynamic loads, resulting in high structural loads, drag, noise and control forces. Especially the pitching moment peaks can cause fatal aeroelastic flutter with negative damping. McCroskey (1981) and Carr (1977) performed comprehensive studies on the phenomenon of dynamic stall and found a concentrated spanwise vortex as the dominant flow structure. In order to reduce the strong impact of dynamic stall on the airfoil’s performance, numerous passive and active dynamic stall control methods have been developed and investigated throughout the last decades (Geissler et al. 1993; Chandrasekara et al. 1998; Carr 1998; Carr 1983; Greenblatt 2001; Post 2004).

Martin et al. (2008) applied counter rotating vane type vortex generators on a pitching VR7 airfoil at Mach numbers between $M = 0.3$ and $M = 0.4$ for various reduced frequencies and two amplitudes ($\alpha_{\text{amp}} = \pm 5^\circ$ and $\alpha_{\text{amp}} = \pm 10^\circ$) at a mean angle of attack of $10^\circ$. The vortex generators were found to have positive effects at lower Mach numbers up to $M = 0.3$ at light stall conditions in terms of maximum lift and in reducing the pitching moment peak. However, they failed for higher Mach numbers and deep dynamic stall cases. By altering the airfoil geometry with a glove and the
application of vortex generators they could improve the performance of the airfoil at high Mach numbers and at deep dynamic stall notably.

Geissler et al. (2005) developed a very simple, retro-fit capable passive device that improves the aerodynamic performance of an airfoil under dynamic stall conditions significantly and only has minor drawbacks for the rest of the envelope. The final dimensions of the patented cylindrical Leading Edge Vortex Generators (LEVoGs) were found after a parameter study (height: 0.5mm, diameter 6mm). In spanwise direction they were spaced equidistantly at 20mm and placed slightly below the leading edge of the airfoil. The LEVoGs were made from self-adhesive rubber and were simply glued onto an existing blade.

Positioned on the stagnation line at moderate angles of attack, the LEVoG’s impact on the flow field is negligible. However, as the angle of attack increases, the stagnation point moves downstream on the lower side. As a consequence, the LEVoGs are exposed to the flow and become active. Mai et al. assumed that the LEVoGs at high angles of attack induce small streamwise vortices that entrain high momentum free stream fluid towards the airfoil’s surface such that the impact of the large scale dynamic stall vortex can be influenced positively. It was found that the less pronounced dynamic stall vortex causes a reduction of the separated flow region which avoids pitching moment peaks and leads to a smaller drag rise (Mai et al. 2006). However, the exact principle of operation of such LEVoGs has not been verified and is an important task in order to further optimize this type of vortex generators.

Previous wind and water tunnel experiments on an OA209 airfoil (Heine et al. 2009) showed that it is a challenging task to investigate the present aerodynamic phenomena with PIV and other methods because of their small scale, unsteady behaviour and intricate optical access. The expected vortical structures have not been found to be stable and well pronounced, but rather to be diffuse and at varying small scales. Due to the limited resolution obtained during the test, a lot of effort was required in order to detect the local effects of the LEVoGs with PIV in wind and water tunnels and several different setups were tested. In none of the experiments actual vortices could be detected, however the significant global impact of the LEVoGs on the flow could be measured and visualized for static and dynamic measurements. Since the previous experiments on static and dynamically pitching airfoils could not satisfactorily contribute to clear the principle of operation of the LEVoGs, more fundamental investigations were performed on a circular cylinder. Williamson (1996), Norberg (2003) and Zdravkovich (1990, 1996) provide a comprehensive review over the flow around cylinders.

Igarashi (1985) investigated the effect of saw tooth roughness elements on the flow around a circular cylinder while he varied height and position of the roughness at Reynolds numbers between $Re_D = 8,700$ and $Re_D = 63,700$. He classified the flow patterns into four regimes according to the state of the boundary layer; each regime showed significantly different aerodynamic properties such as the Strouhal number, drag coefficient or RMS fluctuating pressure. Igarashi also found a roughness Reynolds number where the used vortex generators became effective depending on the device height, position and free stream velocity.

Triangular vane type vortex generators on a circular cylinder at Reynolds numbers between $Re_D = 50,000$ and $Re_D = 400,000$ were studied by Johnson et al. (1969). The azimuth angle of the vortex generator array was varied between 20° and 80° while drag measurement and flow visualizations were performed. As in the previous study, the drag of the cylinder could be significantly reduced. For example, at a Reynolds number of $Re_D = 220,000$ as used in the present study, and an angular position of the vortex generators of 30°, drag was reduced by 50% compared to the clean cylinder. Johnson et al. summarize, that the closer the generators are to the front of the cylinder, the higher the Reynolds number at which the drag coefficient begins to fall. Also, the higher the Reynolds number, the lower the minimum obtainable drag.

Ünal et al. (2009) investigated the effect of vortex generators on a circular cylinder at a subcritical Reynolds number of about $Re_D = 41,000$ by means of PIV measurements. The rectangular,
counter rotating vanes were tested in a water tunnel at various azimuth angles and a significant impact on the flow was found. The separation was delayed, while the width of the recirculation area was reduced and the length increased. The more slender near wake resulted in lower drag. It was found that the vortex formation length was increased and the strength of the forming vortices was reduced. In addition, it could be demonstrated that the high Reynolds stress regions were moved downstream by the vortex generators.

The aim of this paper is to clear the principle of operation of the circular low profile LEVoGs. The previously conducted experiments (Mai et al. 2006, Heine et al. 2009) with such vortex generators couldn't sufficiently contribute to explain the aerodynamic mechanisms leading to the significant improvements reported by the aforementioned authors. Applied on the well studied geometry of a circular cylinder, a better understanding of the local aerodynamics was expected. Parameters such as the Reynolds number or the boundary layer thickness at the vortex generator position could easily be adjusted by simply changing the azimuth angle of the vortex generators without changing the diameter based Reynolds number Re_D. Taking advantage of a wide range of measurement and flow visualization techniques such as stereo particle image velocimetry (sPIV), surface pressure measurements, infrared thermography and oil flow visualization, the flow was studied thoroughly. In addition, powerful analysis methods such as the proper orthogonal decomposition were applied to the data gained from the experiments. In general, studies about vortex generators applied on circular cylinders employing modern measurement methods such as stereo PIV are rare and the present paper can contribute to understand the complex flow.

2. Experimental Setup

Experiments were conducted in the closed-circuit low-speed wind tunnel (1MG) at the DLR in Göttingen. It has an open test section with dimensions 1.0m x 0.7m x 1.4m (W x H x L). The tunnel allows for a range of subsonic velocities from U_∞ = 0 - 55 m/s at a turbulence level of Tu = 0.15 %.

In order to obtain a similar boundary layer thickness and Reynolds number based on the distance between the stagnation line and the LEVoG position as on previously performed experiments on the OA209 airfoil (Mai et al. 2006), the free stream velocity had to be high. Due to a preset cylinder diameter and the maximum velocity of the wind tunnel, the Reynolds number was set to 220,000 for all experiments. This is the high sub-critical Reynolds number regime, where a twin separation line is present (Dallmann et al. 1987).

For all measurement techniques the azimuth angle of the vortex generators was modified in 2° steps from -20° regarding the first stagnation line to at least 130° in clockwise direction. For both, the PIV and the pressure measurement, two configurations for each case were measured: One with a LEVoG in the measurement plane and one with the measurement plane between two LEVoGs.

2.1 Wind tunnel models

Two different cylinder models were used. Both had a diameter of 60mm and a length of 764mm. End plates with a diameter of 500mm were used on both sides of the cylinder to avoid tip leakage. Kubo et al. (1989) suggested an optimal diameter of the end plates of about 8.5 times the model depth which is close to the ratio of 8.3 that was used in the present study. The aspect ratio Λ based on the model span between the end plates and the cylinder diameter was 12.7 which is sufficient to obtain span-independent results (Szepessy et al. 1992). The blockage of the cylinder in the test section was 8.6%, which is sufficiently small to abdicate wind tunnel corrections (Zdravkovich 2003). For the experiments with vortex generators a row of LEVoGs was glued onto the cylinder with the size and spacing as suggested in Mai et al. (2006). The azimuth angle Φ_L of the vortex generators was then altered by simply rotating the cylinder.
A smooth black aluminum cylinder was used for PIV measurements, infrared thermography and oil flow visualization. In order to increase temperature gradients for the infrared measurements, the cylinder was equipped with an internal 900W heating element and a controller to adjust the surface temperature.

The second cylinder model was used for steady and unsteady surface pressure measurements. It was equipped with 48 pressure ports (26 at the cylinder center perimeter) for steady, and 24 Kulite pressure transducers (4 at the cylinder center perimeter) for unsteady pressure measurements. The signals from the unsteady pressure ports were recorded at a sampling rate of 4000Hz for a duration of 5s.

2.2 Measurement techniques

For the investigation of the flow field, stereoscopic particle image velocimetry measurements were performed in a plane perpendicular to the cylinder axis in the center of the model. Figure 1 depicts the setup of the experiment. For the light sheet, a frequency doubled Nd:YAG laser with a pulse energy of 360mJ and a lens system was used. DEHS aerosol particles were generated by a Laskin nozzle particle generator and had a mean diameter of 1µm. Two CCD cameras with a resolution of 4008 x 2672 px$^2$ positioned at a 49° angle towards the light sheet on opposite sides were used with Scheimpflug adapters. In order to be able to focus on the object plane, two Scheimpflug adapters were used. The recorded field of view was 264 x 177mm$^2$ with a resolution of about 15px/mm. For statistical purposes, 500 images at a recording rate of 0.5Hz were taken for every test case. The double images were evaluated using a multi-grid algorithm with grid refinement and a final interrogation windows size of 32 x 32 px$^2$ with an overlap of 66%, resulting in a field of 361 x 240 vectors.

![Fig. 1 Setup of the wind tunnel experiment with light sheet position](image)

For the investigation of the surface flow, oil flow visualization and infrared thermography were employed. The oil flow visualization was performed with a mixture of titanium oxide and kerosene.

Infrared thermography was done with a long wave infrared camera with a thermal resolution of 0.05K with a spatial resolution of up to 1280 x 960 px$^2$. The infrared camera system was used to observe the influences of the LEVoGs on transition and flow separation, which is possible due to the Reynolds analogy since the heat transfer of a surface is proportional to the wall shear stress. Before each wind tunnel run, the cylinder was heated to a temperature that was about 45K higher than the ambiance (wind off). Before and during the run several images were taken. By subtracting
the no-wind image where the temperature distribution was uniform, the different flow conditions on the cylinder surface could be extracted. It should be mentioned that even though the camera would allow a recording rate of up to 50Hz, the thermal capacity of the cylinder was high and hence wouldn't allow for real instantaneous measurements.

Besides the aforementioned optical methods, surface pressure data was also recorded using the second wind tunnel model. Since the model was initially designed for a different experiment, only 4 unsteady and 24 steady pressure ports were available at the cylinder circumference at mid-span. To obtain a sufficient resolution of unsteady pressure measurements over the circumference, the cylinder therefore had to be rotated. By analyzing the temporal signals of the pressure transducers with a Fast Fourier Transformation (FFT), the Strouhal number was extracted from the pressure signal.

3. Results and Discussion

All above mentioned measurement techniques were used to investigate the flow around the cylinder at a free stream velocity of 54.5m/s, resulting in a low subsonic Mach number of $M = 0.15$ and a high sub-critical Reynolds number of $Re_D = 220,000$. The analysis of the measurements discussed below allows for a categorization of the flow into 3 flow conditions, listed in table 1:

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\Phi_L$ range</th>
<th>Flow pattern</th>
<th>$-c_{p\text{min}}$</th>
<th>lam. separation</th>
<th>turb. separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>clean</td>
<td>-</td>
<td>stable</td>
<td>1.18</td>
<td>71°</td>
<td>80°</td>
</tr>
<tr>
<td>I</td>
<td>$6° \leq \Phi_L \leq 15°$</td>
<td>bundling</td>
<td>1.3 - 1.6</td>
<td>74° - 81°</td>
<td>~90° - ~130°</td>
</tr>
<tr>
<td>II</td>
<td>$15° \leq \Phi_L \leq 78°$</td>
<td>stable</td>
<td>1.6 - 2.35</td>
<td>81° - 88°</td>
<td>110° - 130°</td>
</tr>
<tr>
<td>III</td>
<td>$78° \leq \Phi_L \leq 90°$</td>
<td>bundling</td>
<td>1.6 - 1.18</td>
<td>86° - 88°</td>
<td>?</td>
</tr>
</tbody>
</table>

3.1 Clean case

Figure 2 depicts an oil flow visualization of the cylinder where the twin separation lines can be seen clearly. The clean configuration showed laminar separation at $\Phi = 71°$ and turbulent separation at $\Phi = 80°$. At $\Phi = 93°$ the separation line for the reverse flow is visible. It can also be seen that the separation lines are straight which indicates two-dimensional flow over the cylinder.

![Fig. 2 Oil flow visualization of the clean configuration. Flow direction is from top to bottom, viewing direction is 90° rotated around the cylinder axis.](image)

The symmetric pressure distribution showed a minimum pressure coefficient of $c_p = -1.2$ at $\Phi = 65°$. Pressure drag coefficient and Strouhal number $St$ were calculated to $c_{d0} = 1.14$ and $St = 0.18$ which is in very good agreement with the results of Bearman (1969) who found a drag coefficient of $c_d = 1.14$ and a Strouhal number $St = 0.18$ at very similar conditions ($Re = 200,000$, $Tu = 0.2\%$, $\Lambda = 12$, $B = 6\%$). It should be noted that the measured drag in the present study is the pressure drag only, according to Zdravkovich (1997) the friction drag is negligible for Reynolds number higher than 40,000.
3.2 Condition I

With the vortex generators placed at an azimuth angle between \(2^\circ \leq \Phi_L \leq 15^\circ\), the flow visualizations indicate weak unsteady three-dimensional structures. Figure 3a) depicts an infrared visualization with the flow direction coming from the top where 22 LEVoGs were placed. The thin dotted lines are drawn along low temperature streaks, originating from the wakes of individual LEVoGs, indicating the strong three-dimensionality of the flow. Figure 3b) shows the temperature difference curves \(\Delta T = T(t_0) - T(t)\) along the cylinder perimeter at two different spanwise stations (1) and (2). The difference in temperature between the red (convergent structures) and the blue line (divergent structures) is visible after the maximum thickness indicating spanwise differences in wall shear stress. Figure 3c) shows the spanwise temperature distribution along the black line in figure 3a). Where the distribution for the clean case was quite constant, strong variations can be found for the case with LEVoGs. Video recordings of this case show that a changing number of individual LEVoG wakes group together as they travel downstream, resulting in the non-uniform temperature distribution in spanwise direction. This phenomenon is in the following referred to as bundling. Note that for very low and very high angles the error is quite large due to the large angle between the infrared camera and the cylinder surface.

![Infrared measurement at \(\Phi_L = 11^\circ\). a) Colour coded infrared image. Flow direction is from top to bottom, viewing direction is 90° rotated around the cylinder axis. b) Temperature-difference distribution curve along cuts (1) and (2). c) Temperature-difference distribution in spanwise direction.](image)

The pressure distribution indicates strong pressure fluctuations around the mean but also spanwise differences. Separation takes place between \(\Phi = 74^\circ\) for \(\Phi_L = 2^\circ\) and \(\Phi = 80^\circ\) for \(\Phi_L = 15^\circ\) while the Strouhal number remains constant at \(St = 0.183\). With the delay of the separation also the minimum pressure coefficients reduces from \(c_p = -1.2\) to \(c_p = -1.4\).

3.3 Condition II

A rather stable flow condition can be found for LEVoGs for azimuth angles between 15° and 78°. The wakes of the vortex generators point straight in flow direction and are stable in size and position. Once the wakes reach the separation line of the undisturbed flow between the generators, a
characteristic interaction was found. Figures 4a) and b) depict results of infrared measurement at while figure 4c) shows an oil flow visualization each for LEVoGs at $\Phi_L = 60^\circ$. The turbulent flow behind the vortex generators is able to persist the adverse pressure gradient longer than the laminar flow between the LEVoGs, allowing the flow to break through the separation line. This results in a region of high shear: while the velocity in the turbulent flow is high, the velocity in the separated region is close to zero. In these regions a steady pair of counter-rotating vortices are formed which could be visualized in figure 4c). Between the wakes of the LEVoGs a laminar separation bubble with later turbulent separation is present. Figure 4b) shows the temperature distribution along two cuts around the cylinder perimeter 1) at the center of a LEVoG, 2) between two LEVoGs. As expected, the heat transfer in the turbulent wake of a LEVoG is higher than for the laminar flow. In the laminar case, the heat transfer reaches a maximum at the position of the vortex. Downstream of the vortex generators at about $\Phi = 105^\circ$ the wall temperatures assimilate again and hence have a similar wall shear. Turbulent separation then takes place at $\Phi = 105^\circ$. This is in good agreement with the pressure measurement. Compared to flow condition I, the minimum pressure fluctuations are much lower. Due to the later separation, the pressure coefficient reduces further, and the Strouhal number increases to a quite constant value of about 0.23.

Johnson et al. (1969) found that the strength of a disturbance created by a vortex generator at the position where separation would normally occur is proportional to the fluid velocity at the vortex generator position. Looking at the clean case, the flow velocity was highest at $\Phi = 65^\circ$. However, when a vortex generator is placed on the cylinder, the area of highest velocities vary between $69^\circ \leq \Phi \leq 75^\circ$, depending on the position of the LEVoG. Hence, to reach the strongest influence of the vortex generator, they should be placed in the mentioned region.

3.4 Condition III

The flow condition for LEVoGs located between $78^\circ \leq \Phi_L \leq 90^\circ$ is dominated by strong unsteady three-dimensional effects. The vortex generators are in the region of the laminar separation line. The wakes of the LEVoGs group together to bundles of six to eight, these bundles are highly unsteady and change their spanwise position and grouping quickly. The stagnation and separation
lines move and the analysis of the unsteady pressure signal reveals that the pressure jumps between at least three levels and remains constant for a short period of time. This behaviour is directly related to the current position of a wake and whether it passes a pressure port or not. Figure 5 a) and b) depicts results of infrared measurements for LEVoGs at $\Phi_L = 85^\circ$ at two different instances in time. The bundling of the LEVoG wakes is clearly visible in both images. Also, the spanwise temperature shows large differences, depending of the positions of the bundles and hence the local skin friction. The shape of the curves in figure 5c) shows how unsteady separation for different instances in time is at the same spanwise position. Figure 5d) shows the spanwise temperature distribution. The bundles in figure 5a) and b) are located where the curves shows low temperature differences. Figure 6 depicts the pressure signal at the maximum thickness for the same case as in Figure 5. The “logging” to different pressure levels, depending on the position of the bundles, is clearly visible.

![Fig 5](image)

**Fig 5** Infrared measurement of flow condition III at two instances in time ($t_1 = 30s$, $t_2 = 60s$). a) and b) Infrared images, c) Temperature measurements along circumference and d) in spanwise direction for $\Phi_L = 85^\circ$.

![Fig 6](image)

**Fig 6** Pressure signal at $\Phi = 90^\circ$ for $\Phi_L = 85^\circ$ during a 5s period
The dominant bundling of the LEVoG wakes found for the application of LEVoGs on the circular cylinder was also seen by Mai et al (2006) during the investigation of LEVoGs on a helicopter airfoil. Figure 7 depicts a result of infrared thermography from this work, the grouping of wakes is clearly visible.

Fig 7 Infrared measurement of an OA209 airfoil at a high angle of attack by Mai et al (2006).

3.5 PIV measurements

Figure 8 depicts streamlines and standard deviation colour contours for the three flow cases described above in the configuration where the light sheet was positioned between two LEVoGs. It becomes clear that by changing the azimuth angle of the vortex generators, the near wake of the cylinder changes dramatically. The magnitude of the velocity fluctuations as well as the dimension of the recirculation bubble change with respect to the current position of the LEVoGs. To compare different measurements to each other, 3 different characteristic length scales were obtained from the PIV data and collected in table 2: The non-dimensional vortex formation length $l_f/D$, the non-

- 9 -
dimensional recirculation bubble length \( l_c/D \), and the non-dimensional distance from the cylinder centroid to the location of the minimum streamwise velocity \( l_u/D \). These length scales are usually measured along the wake center line. Since the wake is not symmetric due to the vortex generators in the present experiments, the values were measured along the center of the wake and the x-component was taken as length scale.

**Tab 2** non-dimensional vortex formation length \( l_f/D \), non-dimensional recirculation bubble length \( l_c/D \) and non-dimensional distance to the minimum streamwise velocity \( l_u/D \)

<table>
<thead>
<tr>
<th>Flow condition</th>
<th>( \Phi_L )</th>
<th>( l_f/D )</th>
<th>( l_c/D )</th>
<th>( l_u/D )</th>
<th>St</th>
<th>( l_f/D )</th>
<th>( l_c/D )</th>
<th>( l_u/D )</th>
<th>St</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6</td>
<td>1.50</td>
<td>1.60</td>
<td>1.05</td>
<td>0.182</td>
<td>1.60</td>
<td>1.87</td>
<td>1.21</td>
<td>0.183</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.28</td>
<td>2.22</td>
<td>1.46</td>
<td>0.182</td>
<td>2.05</td>
<td>2.13</td>
<td>1.46</td>
<td>0.184</td>
</tr>
<tr>
<td>II</td>
<td>37.5</td>
<td>1.76</td>
<td>1.85</td>
<td>1.23</td>
<td>0.231</td>
<td>1.75</td>
<td>1.84</td>
<td>1.32</td>
<td>0.228</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>2.01</td>
<td>1.90</td>
<td>1.28</td>
<td>0.231</td>
<td>1.95</td>
<td>1.98</td>
<td>1.33</td>
<td>0.230</td>
</tr>
<tr>
<td>III</td>
<td>85</td>
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<td>2.44</td>
<td>1.41</td>
<td>--</td>
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<tr>
<td></td>
<td>90</td>
<td>2.12</td>
<td>2.20</td>
<td>1.46</td>
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<td>1.65</td>
<td>1.91</td>
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<td>--</td>
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<td>1.07</td>
<td>0.180</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Fig 9** a) Characteristic non-dimensional length scales \( (l_f/D, l_c/D \) and \( l_u/D \)) over the azimuth angle of the vortex generators. The dotted line depicts the values for the clean cylinder. b) The Strouhal number over the azimuth angle of the vortex generators.

Figure 9 depicts the dependency of the characteristic length scales from the azimuth position of the LEVoGs and confirms the classification in three different flow conditions. At low azimuth angles of the vortex generators \( \Phi_L \leq 6^\circ \), the length scales are nearly unchanged compared to the clean case, also the velocity fluctuations and the pressure distribution remain close to the clean cylinder case. Is the azimuth angle of the LEVoGs set to the flow conditions I or III where bundling of the wakes is present, the length scales show an increase. In between these two flow conditions the values of the length scales decrease again. The Strouhal number shows an adverse behaviour: While the vortex shedding frequency is high in flow condition II, the length scales are rather small. A similar increase of the Strouhal number was observed by Igarashi (1985) for various Reynolds numbers and vortex generator heights. He claimed that in the region of increasing Strouhal number the onset of boundary layer transition takes place in the boundary layer. In the region where the Strouhal number is nearly constant, he assumed laminar-turbulent transition occurs in the boundary layer which is accompanied with a reduction in wake width and drag coefficient. When flow separation without reattachment occurs due to the presence of the vortex generators, the Strouhal number drops below the value of the clean configuration. Hoerner (1965) found a relation between the Strouhal number and the drag coefficient for circular cylinders:
\[ \text{St} = 0.21/c_d^{0.75} \]  

This is in good agreement with the pressure drag measurements performed in the current experiment. For the clean configuration a deviation of 5% for the Strouhal measurement and 7% for the drag measurement was found. In flow condition II, the deviation was 1% for the Strouhal number and 2% for the drag respectively.

Also a very similar behaviour to the one shown in figure 9, was found analyzing the standard deviation of the surface pressure signals. For high azimuth angles where the vortex generators do not disturb the measurement itself, the signal fluctuations were highest for flow condition I and beginning of III while the values were lower in flow condition II. Igarashi (1985) found that the pressure fluctuations are directly related to separation and drag. He concluded that low RMS values result in late separation and low drag while the effects invert for high RMS values.

Figure 10 depicts time averaged \( \zeta_z \)-vorticity \( \zeta_z = \partial V/\partial x - \partial U/\partial y \) plots for LEVoGs at \( \Phi_L = 37.5^\circ \) and \( \Phi_L = 85^\circ \). The black contour line, corresponding to the lightest blue and red tones in the present plot, depicts the same vorticity intensity of the clean case. It can be seen that for both cases the region of high vorticity is elongated compared to the clean case. This effect was pronounced for flow conditions I and III. For flow condition II it was found that the transverse dimension was reduced and that the regions of high vorticity moved closer to the center of the wake. For flow conditions I and III, the opposite was the case; the high vorticity region moved away from the wake center line and the vorticity region widened in transverse direction.

3.6 POD Analysis

For further analysis of the data obtained from the PIV measurements, the Snapshot Proper Orthogonal Decomposition (POD) method developed by Sirovich (1987) was used for post processing. Figure 11 depicts the energy spectra for the LEVoGs at all measured azimuth angles and at the plane in the center between two LEVoGs and the plane in the middle of a LEVoG. Therefore the eigenmodes of the correlation matrix were calculated. The first seven modes, especially the two first, are very dominant and contain already 60% of the total flow energy for the clean case (mean flow subtracted). These first few modes represent the contribution of the large scale periodical motion to the total fluctuating energy. It is obvious that for all cases the lower modes of the clean configuration contain more energy than those of configuration with LEVoGs. It can be concluded that the vortex generators increase the contribution of smaller fluctuations to the total flow energy. Apparently the vortex generators seem to break large coherent structures into smaller ones. This was also observed by Ünal et al. (2009) and Heine et al. (2009).
In order to separately investigate the effects of the vortex generators on both the large scale coherent structures and the random fluctuation, the flow fields were reconstructed by only using the seven most energetic modes or all modes without the first seven respectively. Figures 12 and 13 depict the reconstructed Reynolds stresses (without density) for the clean case and two different vortex generator positions of flow condition II and III. While figure 12 shows the most energetic coherent structures of the first seven modes, figure 13 depicts the random (low-energetic) structures.

By comparing the clean case a) with the $\Phi_L = 37.5^\circ$ LEVoG case b), it can be seen that the coherent
motion of the high energetic modes was dampened significantly and that the high normal and shear stress regions are located further downstream. This trend continues for the $v'v'/U_\infty^2$ and $u'v'/U_\infty^2$ components of the $\Phi_L = 85^\circ$ LEVoG case. However, the region of high $u'u'/U_\infty^2$ normal stress is increased drastically on the upper side of the cylinder where the LEVoGs were placed.

A similar behaviour was found for the randomly fluctuating modes in figure 13. The normalized peak Reynolds stresses are about a factor 3 lower than for the periodic part. It should be mentioned that the turbulent structures could not be resolved by the low recording rate of 0.5Hz and hence a reduction of the random motion does not necessarily mean a reduction in turbulence. The decrease in the stress components may be a result of a stronger three-dimensionality in the flow caused by the LEVoGs. Under such conditions vortex stretching may be present, causing the turbulent length scales to decrease. This may result in a decreased turbulent energy due to the dissipation of turbulence in the smallest scales. It should be noted that for flow condition II, vorticity, shear and normal stress as well as velocity fluctuations are lower than for the clean case and flow condition I and III. This indicates lower drag.

![Normalized time-averaged Reynolds stress-fields of the low-energetic modes starting from mode 8 (random components). Left column: $u'u'/U_\infty^2$ Center column: $v'v'/U_\infty^2$ Right column: $u'v'/U_\infty^2$. a) clean configuration, b) $\Phi_L = 37.5^\circ$ and c) $\Phi_L = 85^\circ$.](image)

5. Conclusions

Leading Edge Vortex Generators, designed for rotorcraft applications, have been found to reduce the impact of dynamic stall significantly but the mode of operations of such devices is unclear. In order to find the origin of the large improvements under dynamic stall conditions, the effects of these circular low profile vortex generators have been investigated on the flow around the well studied shape of a circular cylinder at a high Reynolds number of 220,000.

Applying LEVoGs to the cylinder, the flow could be classified into 3 regimes, depending on
the azimuth angle of the vortex generators. While the flow around the cylinder behaved similar for flow condition I and III, condition II for moderate azimuth angles showed clearly different aerodynamic properties.

Bundling of the vortex generator wakes for flow condition I and III was detected by oil film visualization and infrared thermography and is in good agreement with the unsteady pressure measurements. This effect was also observed on an OA209 rotorcraft airfoil at high angle of attack (Mai et al. 2006, Heine et al. 2009). The bundling in the present study has also been observed at different Reynolds numbers and is not a specific phenomenon of the current Reynolds number.

The surface pressure distribution showed, that the LEVoGs alter the pressure distribution from the 'transition in wake' to 'transition in boundary layer' regime. The differences between measurements behind or between a LEVoG were small in terms of minimum pressure coefficient, base pressure and pressure fluctuations. However, for the measurement between the LEVoGs a separation bubble plateau could be detected.

An analysis of the normal and shear stresses showed that the vortex generators reduce the Reynolds stresses when applied at increasing azimuth angle. One exception is the normal stress $u'u'/U_{∞}^2$ for the periodic part of flow condition I and III where the bundling is present. Since for this stress the random contribution is quite similar to the clean case, the vortex generators seem to nearly exclusively influence the periodic or large scale motion of the wake for this component.

For flow condition II (LEVoGs at $15° ≤ Φ_L ≤ 78°$) where the velocity at the vortex generator is high, one main effect of the vortex generators might be that the flow gets accelerated further between two LEVoGs. The accelerated flow is able to overcome a stronger adverse pressure gradient, resulting in delayed separation. This is the same effect as if the Reynolds number had been increased. At the same time the wakes of the LEVoGs are turbulent, also allowing the flow to stay attached longer. Between the laminar and the turbulent wake, a pair of counter rotating vortices settled. Behind the laminar separation line of the flow between two LEVoGs, the effects mix, leading to a common turbulent separation. All Reynolds stresses as well as the vorticity are reduced while the shear layer moves closer to the wake center line. Reduced Reynolds stresses and vorticity result in a reduction of drag which could be demonstrated for flow condition II. Here the pressure drag was reduced by 25% compared to the clean case.

At flow condition III (LEVoGs at $78° ≤ Φ_L ≤ 90°$), the deceleration of the boundary layer amplifies instabilities that might be triggered by the LEVoGs and cause the bundling. The spanwise disturbances observed by Higuchi et al. (1988) and Humphreys (1960) at critical Reynolds numbers of a cylinder flow might also support the bundling. Similar spanwise structures on a two-dimensional wing have been observed among others by Schewe (2001).

The mechanisms of flow condition I (LEVoGs at $6° ≤ Φ_L ≤ 15°$) remain unclear. Even so accelerated boundary layers dampen instabilities, bundling is still present even though not as excessive as for flow condition III. However, the effects on the flow remain the same for condition I and III.

The LEVoGs do not seem to introduce a large out of plane component. It remarkable that for all flow conditions the average axial velocity and axial fluctuations are lower than for the clean configuration. Hence the vortex generators rather seem to have stabilizing effect on this flow component.

In order to exclude the various complicated effects of the transcritical cylinder flow, future experiments should be performed in the supercritical regime where a clear separation bubble and turbulent separation is present. In addition, a symmetrical placement of the vortex generators on both sides of the cylinder would remove asymmetry and facilitate the analysis of the measurements. In order to better resolve spanwise effects, PIV measurements should also be performed in a plane parallel to the cylinder axis and perpendicular to the free stream. Further, for a complete fluctuating lift and drag analysis, unsteady pressure sensors around the circumference would be desirable.
References

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