High-speed PIV measurements of the influence of artificial surface structures on the near-wall flow field of 3D wing models based on an owl geometry

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Abstract The geometry of the barn owl wing, i.e., the planform, the camber line, and the thickness distribution, differs significantly from the wing geometry of other bird species of comparable weight and size. To investigate the flow field of this special geometry with its distinct nose region and large thickness in context with a small chordwise position of the maximum thickness, technical wing models based on the barn owl wing were designed. The influence on the flow field of one of the owl-specific adaptations, namely the velvet-like surface structure on the suction side of the wing, was analyzed via high-speed particle-image velocimetry (PIV). Measurements were performed in a Reynolds number range of $40,000 \leq \text{Re}_c \leq 120,000$ and angles of attack of $0^\circ \leq \alpha \leq 6^\circ$. The first artificial surface structure, referred to as velvet 1, was selected to imitate the hair length, density and thus, the softness of the natural surface. Velvet 2, the second artificial surface, possesses longer, softer filaments and a preferred hair direction. A strong influence of the surface structures on the flow field was found for both velvet structures. The velvets seem to force the laminar to turbulent transition in the free shear layer at higher Reynolds numbers and thus, enable the flow to reattach earlier. This leads to a reduction of the separation bubble on the suction side of the wing.

1. Introduction

The barn owl is a well-known example for a biological system that possesses a high level of adaptation to its habitat, since it has evolved hunting strategies that depend on the localization of the prey via its binaural hearing sense. Therefore, the barn owl has developed special adaptations on its wings and plumage to fly silently to, on the one hand, detect its prey, and, on the other hand, be inaudible to the prey during hunting. According to Mebs and Scherzinger (2000), the barn owl approaches its prey in gliding flight at relatively low speeds of 2.5 m/s to 7.5 m/s which correspond to Reynolds numbers of 30,000 to 90,000. Hence, the low flight speed might be one of the main features of the owl’s silent flight. Although flow phenomena such as separation are likely to occur in this low-Reynolds number regime, leading to lift reduction, drag increase, and pressure fluctuations as stated by McMasters and Henderson (1980), some animals successfully fly at Reynolds numbers $\leq 100,000$.

The geometry of the barn owl wing indicates that it is designed especially for low-speed gliding flight. Its shape is characterized by an almost elliptical planform and a wing size that is larger than that of birds of comparable weight, e.g., the pigeon. According to Klän et al. (2008), the strong camber and the drip nose geometry of the owl wing lead to an extended suction area near the leading edge of the wing. The adaption of the owl to silent low-speed gliding flight provides potential for technical applications such as Micro Air Vehicles (MAV’s).

Additionally to the geometrical features of the wing, three special adaptations of the owl wing, namely the leading-edge serrations, the trailing-edge fringes, and the velvet-like surface structure were identified by Graham (1934). The velvet-like surface structure is caused by the elongated pennula on the suction side of the wing. As discussed by Klän et al. (2008), a laminar separation bubble caused by the adverse pressure gradient due to the curvature of the wing is likely to occur at approximately 20\% chord for the aforementioned wing geometry downstream. Video recordings of barn owls in gliding flight show that the surface feathers in the region with a high curvature, i.e., the
arm section, tend to flutter, indicating the presence of a separation bubble at this location. As mentioned above, a separation bubble on the suction side of the wing strongly reduces its aerodynamic performance due to the loss of lift and the increase of drag. Thus, the avoidance or control of the separation is essential for the efficient and silent flight of the owl. It is assumed that the owl-specific adaptations have a positive effect on the size of the separation bubble and hence, enable the owl to perform silent, highly maneuverable low-speed gliding flight.

It is well known that surface structures influence the near-wall flow field of a wing. Therefore, it is expected that the particular surface structures of the owl wing directly affect its aerodynamic performance by influencing the size and position of the separation bubble. According to Klän et al. (2012) the velvet surface structures directly influence the size of the separation bubble by shifting the point of reattachment further upstream. Additionally, it was shown by the spatial two-point correlation of the velocity fluctuations normal to the wall that the size of the vortices shed at the end of the separation bubble and the distance between two consecutive vortices decrease when the velvet-like surface structures are applied to the wing.

To further investigate the influence of the surface structures on the near-wall flow field, high-speed particle-image velocimetry (PIV) measurements are performed. This measurement technique allows the detailed time-resolved analysis of the turbulent flow structures and the investigation of the mechanisms leading to the forced laminar-turbulent transition. Due to the time-resolved measurements, the tracking of turbulent eddies and thus their temporal and spatial development can be detected and analyzed in detail. The power spectral density distribution of the wall-normal velocity fluctuations $v'$ is used to analyze the frequency spectrum and the energy transfer from the large to the small length scales. Furthermore, the space-time correlation of $v'$ reveals the convection velocity of the large scale turbulent structures. Additionally, the integral turbulent length scale $\Lambda$, which is a measure of the extent of the region over which velocities in the flow can be assumed correlated, is analyzed as a function of the applied velvet surface structure.

2. Experimental setup

The experiments were performed in the low speed wind tunnel of the Institute of Aerodynamics. The open test section possesses a rectangular shape with a cross-section of 800 mm $\times$ 800 mm and a maximum freestream velocity of approximately 35 m/s. This large text section was required to ensure an undisturbed flow on the tip of the 3D wing model. The half-span of the wing model is $b/2 = 431$ mm. Thus, the projected distance between the upper edge of the wind tunnel nozzle and the tip of the wing model was 369 mm. Therefore, the influence of the nozzle contour on the flow field was considered to be negligible. The freestream turbulence level was $Tu \approx 0.7\%$. The flow on the ground plate was tripped by a 0.5 mm wire to ensure a turbulent boundary layer.

Since the chord length of the 3D wind tunnel model varies significantly in spanwise direction, the Reynolds numbers were calculated based on the average chord length of the inner 40% of the span, which is $c = 178$ mm. Assuming an almost elliptical lift distribution, this area provides approximately 50% of the total lift force of the wing. This leads to Reynolds numbers of $Re_c = 4\cdot10^4$, $6\cdot10^4$, and $1.2\cdot10^5$ for freestream velocities of $u_\infty = 3.5$, 5.3, and 10.5 m/s, respectively. The measurements were conducted at angles of attack of $\alpha = 0^\circ$, $3^\circ$, and $6^\circ$. To investigate the influence of the three-dimensionality of the wing model on the flow field, four spanwise positions, namely $2y/b = 0.12$, 0.20, 0.25, and 0.30 were chosen. The measurement planes were parallel to the mounting plate of the wind tunnel, i.e., aligned with the flow direction and normal to the center plane of the wing. It is known that at low Reynolds numbers the flow field around a wing model might encounter hysteresis effects, leading to a strong alteration of the flow field even if the changes in the angle of attack are small. To avoid this kind of artificial impact on the flow field, the wind tunnel was turned off after each measurement before the angle of attack was changed for the new measurement configuration. The combinations of the listed parameters surface, spanwise
position, angle of attack, and Reynolds number lead to 108 parameter combinations that were investigated. A complete overview of all measured configurations is given in tab. 1.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Spanwise position $2y/b$ [-]</th>
<th>Angle of attack $\alpha$ [°]</th>
<th>Reynolds number $Re_c$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>0.12</td>
<td>0</td>
<td>40,000</td>
</tr>
<tr>
<td>Velvet 1</td>
<td>0.20</td>
<td>3</td>
<td>60,000</td>
</tr>
<tr>
<td>Velvet 2</td>
<td>0.25</td>
<td>6</td>
<td>120,000</td>
</tr>
</tbody>
</table>

2D-2C high-speed particle-image velocimetry (PIV) was used to analyze the flow field. The experimental setup comprised a Quantronix Darwin Duo high-speed laser, light sheet optics, and a Photron SA3 CMOS high-speed camera. An ILA high-speed synchronizer provided the trigger signal for laser and camera. The sampling frequencies were 2000 Hz for the measurements performed at $Re_c = 4 \cdot 10^4$ and $6 \cdot 10^4$, and 4000 Hz for $Re_c = 1.2 \cdot 10^5$, respectively. For each configuration 1000 images were recorded. This number was sufficient to obtain converging statistics of the unstable flow field. DEHS droplets generated with a Laskin-nozzle seeder were used as seeding particles. The post-processing was done using the PivTec / ILA GmbH software PivTecIla. The size of the final interrogation window was 24 px $\times$ 24 px with an overlap of 12 px, i.e., 50 %, in horizontal direction and 16 px $\times$ 16 px with an overlap of 8 px in vertical direction. A schematic of the experimental setup is given in fig. 1.

The natural surface of the wing is characterized by approximately 200 hairs per mm$^2$ with a mean diameter of $d \approx 6 \mu$m. These hairs tend to stick together and form bundles. To investigate the influence of these hairs on the flow on the suction side of the wing, the 3D wing models were equipped with two different artificial surfaces structures. Since the tendency to stick together is difficult to imitate by artificial structures, two synthetic velvet-like tissues were selected to mimic this behavior. The first velvet, in the following referred to as “velvet 1”, was chosen to emulate the natural surface with respect to the length, density, and softness of these hairs. After horizontal deflection, the hairs return to their vertical orientation within 10 ms.
The second velvet, denoted as “velvet 2”, possesses longer hairs and thereby is softer than the natural surface or “velvet 1”. Moreover, this velvet has a uniform preferred hair orientation that is aligned with mean the freestream direction. When the hairs of velvet 2 are deflected to a horizontal position in their preferred direction, they tend to stick to the surface. Similarly to velvet 1, the hairs return to their vertical orientation within 10 ms when deflected in the opposite than the preferred hair direction. The reset time for the natural surface could not be measured. Figure 2 shows photographs of the natural and the artificial surface structures, tab. 2 summarizes the properties of the three different surface structures.

**Tab. 2.** Properties of the natural surface of the wing and the two artificial surface structures.

<table>
<thead>
<tr>
<th></th>
<th>Density [n/mm²]</th>
<th>Length of hairs [mm]</th>
<th>Thickness of hairs [µm]</th>
<th>Reset time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>≈ 200</td>
<td>1.0</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Velvet 1</td>
<td>≈ 190</td>
<td>1.5</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>Velvet 2</td>
<td>≈ 160</td>
<td>2.4</td>
<td>10</td>
<td>∞, 10</td>
</tr>
</tbody>
</table>

It is beyond the scope of this work to explicitly present all averaged flow fields at any configuration, listed in table 1. Therefore, only two parameter combinations of Reynolds number, spanwise position, and angle of attack, were selected based on their representativeness of the effect of the surfaces on the flow field. That is, these cases emphasize the effect of the three surface structures on the spatial and temporal evolution of the main flow phenomena.

**Tab. 3** Overview of the surface structures, spanwise positions, and free stream conditions for configurations (b) and (c).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Surface</th>
<th>Spanwise position 2y/b [-]</th>
<th>Angle of attack α [-]</th>
<th>Reynolds number Re_c [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (b)</td>
<td>Clean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1 (b)</td>
<td>Velvet 1</td>
<td>0.12</td>
<td>3</td>
<td>60,000</td>
</tr>
<tr>
<td>V2 (b)</td>
<td>Velvet 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (c)</td>
<td>Clean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1 (c)</td>
<td>Velvet 1</td>
<td>0.20</td>
<td>0</td>
<td>40,000</td>
</tr>
<tr>
<td>V2 (c)</td>
<td>Velvet 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first configuration which was selected for detailed analysis was the flow field at 2y/b = 0.12, a Reynolds number of Re_c = 60,000, and an angle of attack of α = 3°. It is referred to as “C (b)” for
the clean case, “V1 (b)” for the model equipped with velvet 1, and “V2 (b)” for the model coated with velvet 2, respectively. Analogously, the flow field at 2y/b = 0.20, Re_c = 40,000, and α = 0°, which is analyzed in depth, is referred to as “C (c)”, “V1 (c)”, and “V2 (c)” for the three surface structures.

3. Results and Discussion

The influence of the velvet-like surface structures on the flow field on the suction side of the wing is analyzed via high-speed particle-image velocimetry (PIV). Two-dimensional velocity fields as well as time-averaged Reynolds shear stresses and spatial two-point correlations are used to visualize the temporal and spatial development of the separation region on the suction side of the wing and the corresponding vortical structures. As far as the vortices are concerned, especially the size, the spacing, and the convection velocity of these structures are of main interest. Note that the results of the model equipped with velvet 2 are preliminary.

The velocity distribution is recorded in vertical measurement planes in the free stream direction (x-z-planes). Two-point correlations were performed for the velocity fluctuations in flow direction u' and perpendicular to the flow direction v', respectively.

The time-averaged Reynolds shear stress is defined as $R_{xy} = \frac{u'v'}{u_x^2}$, where $u_x$ is the freestream velocity and $u'$ and $v'$ represent the velocity fluctuations in the streamwise and the perpendicular flow direction, respectively. The distribution of the shear stress describes the momentum transfer into the boundary layer (Yuan et al., 2005). Following Burgmann et al. (2008), the transition onset is determined as the point where a significant rise of the shear stress above the noise level is detected.

Spatial two-point correlations of the normal velocity fluctuations $v'$ were used to analyze the flow phenomena around the wing. The distribution of the local maxima and minima in this two-point correlation indicates the average streamwise extent of a shed vortex and the distance between two consecutive vortices (Kim et al., 1987). The two-point correlation of the wall-normal velocity fluctuations are calculated by

$$r_{wy} = \frac{v'(\bar{x})v'(\bar{x} + \Delta \bar{x})}{v'(\bar{x})^2},$$

where $v'$ is the normal velocity fluctuation at the reference position, which is denoted by the vector $\bar{x}(x, y)$. The two-point correlations show a two-dimensional distribution since $\Delta \bar{x}$ depends on the x- and y-coordinates.

Figures 3 and 4 show the mean values of the axial velocity component for the two configurations (b) and (c). To compare the size of the main flow phenomena, all vector fields in figs. 3 and 4 were rotated counter clockwise, so that the surface of the wing profile is parallel to the x-axis of the coordinate system. The white regions below the trailing edge indicate areas where due to the rotation, no flow velocities could be calculated.

The clean wing configuration shows comparable flow fields for both parameter combinations. For both cases, a separation bubble, i.e., a flow separation near the leading edge with a subsequent reattachment, forms on the suction side of the wing. The size of this separation bubble is $l_b/c \approx 0.23$ for case C (b) and $l_b/c \approx 0.28$ for case C (c), respectively, where $c$ represents the chord length. Its position is located at $0.20 \leq x/c \leq 0.43$ for configuration C (b) and $0.25 \leq x/c \leq 0.52$ for configuration C (c).

The same flow phenomenon can be found for the wing model equipped with velvet 1. Note that the wall-normal extension of the bubble is reduced at both configurations V1 (b) and V1 (c) in comparison to the clean case and that the separation bubble length is approximately the same for the
former case and decreases for the latter case, respectively. The normalized separation bubble lengths $l_b/c$ are summarized in tab. 4 for all configurations.

![Fig. 3](image-url) Average velocity field at $2y/b = 0.12$ for $Re_c = 60,000$, $\alpha = 3^\circ$ for the clean (top), velvet 1 (center), and velvet 2 (bottom) configuration.

The flow field at this specific configuration around the model covered with velvet 2 could not be recorded in the direct vicinity between $0.25c$ and $0.5c$ of the wing due to strong reflections caused by the bright color of the artificial surface. Hence, it cannot be directly determined whether or not a separation bubble occurs for this case. Note that the analysis of the flow field around the reflection is not impaired.

The chordwise shear stress distributions for the two parameter configurations are presented in fig. 5. According to Burgmann et al. (2008), the transition onset can be detected by a significant increase of the maximum Reynolds shear stress. For both parameter combinations, the flow around the clean wing model shows the strongest increase of the Reynolds shear stresses. This is caused by the greater wall-normal extent of the separation region as displayed in figs. 3 and 4. For case C (b) the maximum Reynolds shear stress starts to increase at approximately $x_{t,s}/c = 0.28$ and reaches its maximum at $x_{t,e}/c = 0.41$ indicating that the transition takes place downstream of the point of flow separation. Hence, a laminar separation bubble with turbulent reattachment can be observed for this parameter configuration.

Case V1 (b), i.e., the model equipped with velvet 1, shows a similar distribution of the maximum Reynolds shear stress as the corresponding clean wing configuration. Nevertheless, the increase of the Reynolds shear stress is significantly smaller compared to case C (b).
Fig. 4 Average velocity field at $2y/b = 0.20$ for $Re_c = 40,000$, $\alpha = 0^\circ$ for the clean (top), velvet 1 (center), and velvet 2 (bottom) configuration.

The V2 (b) configuration shows a first local maximum at $x_{ts}/c = 0.30$. This first peak is followed by a second, stronger peak further downstream at approximately $x_{ts}/c = 0.45$. This distribution of the shear stresses shows that a first transition onset is caused by the surface structure. The second peak indicates towards the presence of a separation bubble which is not clearly visible in the average flow field due to the reflections mentioned above.

Fig. 5 Maximum Reynolds shear stress distribution for the clean, velvet 1, and velvet 2 configuration at $2y/b = 0.12$ for $Re_c = 60,000$, $\alpha = 3^\circ$ (left) and $2y/b = 0.20$ for, $Re_c = 40,000$, $\alpha = 0^\circ$ (right).

For configuration (c) it has to be noted that the decay of the Reynolds shear stresses is very strong
for the clean wing case. The long but thin separation bubble leads to a quick transition to turbulent flow. At chordwise positions further downstream an equilibrium boundary layer is evidenced for all three surfaces. That is, the maximum shear stress remains more or less constant in the streamwise direction. The positions of the transition onset are summarized in tab. 4 for all configurations.

Figures 6 and 7 show the spatial two-point correlation $r_{vv}$ of the velocity fluctuations normal to the wall $v'$ for both parameter configurations. The spatial two-point correlation $r_{vv}$ is a useful means to analyze the average streamwise extent of a shed vortex and the distance between two consecutive vortices. A chordwise reference position of $x_{rp} \approx 0.7c$ was chosen for the analysis of the vortical structures because this is located downstream of the separation bubble for all flow cases. The reference position $y_{rp}$ is located approximately $\delta/2$ above the wing surface for all cases, with $\delta$ as the local boundary layer thickness at the reference position $x_{rp}$. The integral turbulent length scale $\Lambda$ are calculated by integrating the decreasing $r_{vv}$ distribution around the reference position within the positive limits. It is a measure for the extent of the region over which it is possible to correlate the velocities. This corresponds to the size of the eddies which carry the bulk of the energy of the turbulent motion.

Figure 6 shows the spatial two-point correlation $r_{vv}$ (top) for configuration (b). The flow around the clean wing model shows structures of circular shape. The corresponding line plot presented in fig. 6 (bottom) shows the value of $r_{vv}$ along a streamline at a wall-normal distance of $y_{rp} = \delta/2$ to have negative correlation of $r_{vv}$. The negative correlation indicates spanwise rollers which are released by the separation bubble. A similar flow pattern concerning the size and shape of the flow structures is found for the velvet 1. The integral turbulent length scale for both cases is approximately $\Lambda \approx 0.4\delta$. Unlike the clean and velvet 1 configuration, the velvet 2 configuration the strength of these spanwise rollers is significantly reduced, since a strong negative correlation is not observed to this extent. This observation is in good agreement with the dominant flow features visible in the average flow field. The integral length scale is approximately $\Lambda \approx 0.4\delta$, which is similar to the two other configurations.

**Fig. 6** Spatial two-point correlation $r_{vv}$ of the wall-normal velocity fluctuations $v'$ (top) and the corresponding distribution of $r_{vv}$ along a streamline parallel to the wing surface (bottom) at $2y/b = 0.12$ for $Re_c = 60,000$, $\alpha = 3^\circ$ for the clean (left), velvet 1 (center), and velvet 2 (right) configuration.

The two point-correlations for the clean surface C (c) displayed in fig. 7 shows a fully decorrelated turbulent flow field where no large streamwise travelling structures can be observed. This is in good
agreement with the strong decay of the streamwise Reynolds shear stress distribution presented in fig. 5. The integral length scale for the clean configuration is approximately $\Lambda \approx 0.4 \delta$ which is smaller than for the two velvet structures. The integral length scales for the two artificial surfaces V1 (c) and V2 (c) are approximately $\Lambda \approx 0.5 \delta$. Moreover, the extent of the region over which the detected eddies can be considered to be correlated is larger compared to the corresponding cases of configuration (b). The absolute values of the integral length scale in mm as well as the integral length scale normalized by the local boundary layer thickness at the reference position are summarized in tab. 4.

Fig. 7 Spatial two-point correlation $r_{vw}$ of the wall-normal velocity fluctuations $v'$ (top) and the corresponding distribution of $r_{vw}$ along a streamline parallel to the wing surface (bottom) at $2y/b = 0.20$ for $Re_c = 40,000$, $\alpha = 0^\circ$ for the clean (left), velvet 1 (center), and velvet 2 (right) configuration.

The power spectral density (PSD) distributions of the wall-normal velocity fluctuations $v'$ of configuration (b) and (c) at the reference position $x_{rp} \approx 0.79 \, c$, $y_{rp} = \delta/2$ are shown in fig. 8. According to fig. 5 the Reynolds shear stress for configuration (b) is highest for the clean wing model. From fig. 8 it can be concluded that the clean configuration possesses the highest energy in the entire frequency range. Moreover, the level of the maximum Reynolds shear stresses at the reference position is alike for the configurations with the two velvets. This is in good agreement with the fact that the power spectral density distributions are similar for higher frequencies. Concerning the frequency range below 130 Hz, velvet 1 (V1 (b)) possesses a lower energy level than the clean (C (b)) and velvet 2 (V2 (b)) configuration. Figure 8 shows that the decay of the energy level for configuration (b) at decreasing eddy size agrees with each other. Thus, the energy transfer from the large to the small scales is similar for all configurations.

For configuration (c), the PSD distribution is alike for the clean (C (c)) and the velvet 2 (V2 (c)) configuration at low frequencies, whereas the energy level of velvet 1 (V1 (c)) is significantly lower. For the velvet surface structures the decay rate is more or less at the same level. However, the clean configuration C (c) possesses a significantly smaller decay rate, which indicates that the turbulent structures have a higher kinetic energy at higher frequencies. Although the shear stress level of configuration C (c) and V2 (c) are similar at the reference position $x_{rp} \approx 0.7 \, c$ illustrated in fig. 5, the PSD distributions show a significant difference at higher frequencies. This might be explained by the fact that the Reynolds shear stresses are calculated with maximum velocity.
fluctuations whereas the spectra are measured at a fixed reference position which might not correspond to the position of the maximum value of $R_{uv}$.

Fig. 8: Temporal power spectral density of the velocity fluctuations $v'$ perpendicular to the flow direction for the clean, velvet 1, and velvet 2 configuration at $2y/b = 0.12$ ($Re_c = 60,000$, $\alpha = 3^\circ$, left) and $2y/b = 0.20$ ($Re_c = 40,000$, $\alpha = 0$, right).

Fig. 9: Space-time correlation of velocity the fluctuations $v'$ for the clean (left), velvet 1 (center), and velvet 2 (right) configuration at $2y/b = 0.12$ for $Re_c = 60,000$, $\alpha = 3^\circ$.

In figs. 9 and 11 the space-time correlations of $v'$ along a streamline which is parallel to the wing surface at a reference position $y_{rp}$ are presented for configurations (b) and (c). A detailed visualization of the space-time correlation for the configuration (b) is given in fig. 10. The horizontal line represents the reference line, whereas the dashed black line indicates the direction of the convection. Thus, the convection velocity can be calculated for all flow cases that show a clear correlation.

Fig. 10: Detail of the space-time correlation of the velocity fluctuations $v'$ for the clean (left), velvet 1 (center), and velvet 2 (left) configuration at $2y/b = 0.12$ for $Re_c = 60,000$, $\alpha = 3^\circ$.

The correlations for all surfaces for configuration (b) show large scale fluctuations which are attributed to large eddies convecting downstream with a convection velocity of approximately 2.0 m/s. This is indicated by the slope of the convection path of the vortical structures. For the clean
configuration C (b) it is possible to correlate the velocity fluctuations from the point of reattachment to a position close to the trailing edge. This is caused by the large separation bubble. For the two velvet structures the correlation is also possible for this range but the correlation level is smaller, which indicates that the structure downstream of the separation bubble decay at a higher rate.

Fig. 11 Space-time correlation of velocity fluctuations $v'$ for the clean (left), velvet 1 (center), and velvet 2 (right) configuration at $2y/b = 0.20$ for $Re_c = 40,000$, $\alpha = 0^\circ$.

For configuration (c) presented in fig. 11 the clean configuration C (c) does not show a traceable large scale structures which evidence a convection velocity. This is in good agreement with the spatial two-point correlation and the corresponding shear stress distribution which indicate a fully turbulent flow field at the reference position. In contrast to C (c), the space-time correlation for V1 (c) and V2 (c) show a clear correlation with higher convection velocities in comparison to configuration (b) which agrees well with the findings for the spatial two-point correlation for configuration (c) given in fig. 7. All values of the convection velocity for the configurations (b) and (c) are given in tab. 4.

Table 4 Values for the separation bubble length $l_b$, position of the transition onset $x_t$, the integral length scales $\Lambda$, and the convection velocity for configurations (b) and (c).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>C (b)</th>
<th>V1 (b)</th>
<th>V2 (b)</th>
<th>C (c)</th>
<th>V1 (c)</th>
<th>V2 (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation bubble length $l_b/c$</td>
<td>[-]</td>
<td>$\approx 0.23$</td>
<td>$\approx 0.25$</td>
<td>n.a.</td>
<td>$\approx 0.28$</td>
<td>$\approx 0.10$</td>
</tr>
<tr>
<td>Transition onset $x_t/c$</td>
<td>[-]</td>
<td>$\approx 0.28$</td>
<td>$\approx 0.26$</td>
<td>$\approx 0.43$</td>
<td>$\approx 0.32$</td>
<td>$\approx 0.45$</td>
</tr>
<tr>
<td>Integral length scale $\Lambda$ [mm]</td>
<td>$\approx 8.7$</td>
<td>$\approx 8.3$</td>
<td>$\approx 9.4$</td>
<td>$\approx 4.3$</td>
<td>$\approx 6.1$</td>
<td>$\approx 6.6$</td>
</tr>
<tr>
<td>Integral length scale $\Lambda/\delta$</td>
<td>[-]</td>
<td>$\approx 0.4$</td>
<td>$\approx 0.4$</td>
<td>$\approx 0.4$</td>
<td>$\approx 0.4$</td>
<td>$\approx 0.6$</td>
</tr>
<tr>
<td>Convection velocity [m/s]</td>
<td>$\approx 1.8$</td>
<td>$\approx 2.0$</td>
<td>$\approx 2.0$</td>
<td>-</td>
<td>$\approx 2.2$</td>
<td>$\approx 2.4$</td>
</tr>
</tbody>
</table>

4. Conclusion

High-speed PIV measurements have been performed to investigate the effect of artificial surface structures on the flow field of wing models, which were based on the geometry of barn-owl wings. This geometry in context with the low flight velocities lead to the occurrence of a separation bubble on the suction side of the wing. This flow phenomenon is known to directly lead to a reduction of aerodynamic performance. Nevertheless, the owl must be able to reduce and control the separation on its wings. One of the special adaptations of the owl wing, i.e., the velvet-like surface structure on the suction side, is assumed to strongly influence the flow field around the wing. To investigate the influence of surface structures on the occurring flow phenomena, two artificial surfaces structures were selected to mimic the natural owl wing.

It was found that the artificial surfaces strongly influence the flow field of the wing model. The extent of the separation bubble normal to the wing surface was significantly reduced for both velvet
structures due to the shift of the transition onset further upstream for higher Reynolds numbers. In some cases the separation bubble was fully eliminated due to this earlier laminar to turbulent transition. For all investigated cases, the level of the maximum Reynolds shear stresses was reduced by the velvet structures compared to the clean model. Additionally, the surface structures also showed an influence on the size and the shape of the flow structures downstream of the separation bubble. Although the integral length scale which is a measure for the size of the eddies which carry the bulk of the turbulent kinetic energy, does not change significantly due to the application of the surfaces, an effect on the distribution of $r_{vv}$ and thus, the strength of the eddies was clearly visible.

The analysis of the power spectral density distribution revealed that the clear configuration possesses the highest energy level in the entire frequency range. Especially in the small scales the energy level differs significantly from the velvet structures. Thus, the surfaces not only influence the absolute level of turbulent kinetic energy in the flow but also the distribution of the energy in the smaller scales.

Using a space-time correlation of $v'$ it was detected that the decay of the vortical structures downstream of the separation bubble is also influenced by the velvet structures. The convection velocity of the eddies is higher for the artificial surfaces which corresponds to the reduction of the dominant features, i.e., the separation bubble. Thus, the velvet-like surface structures show a strong influence on the flow field and the corresponding flow phenomena. The reduction of the size of the separation region might increase the aerodynamic efficiency of the wing model. To further investigate the influence of the surface on the aerodynamic performance, force and moment measurements of the different wing models will be conducted.

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6. References