Experimental Analysis of the Flow over an Owl-shape based Airfoil

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Abstract Since noise emission of starting and landing aircrafts is a major problem for modern airports, it is necessary to put more effort into the research how noise can be reduced sufficiently. An example of effective noise reduction in nature is the barn owl. It is known for long, that the wings of barn owls possess a very unique geometry and special structures, such as leading edge serrations, velvet-like surface, and trailing edge fringes. Those owl-specific characteristics have an influence on the overall flow field and, thus, on the noise emission of the wing. To investigate their impact on the flow field, it is necessary to have a wing whose geometry is based on the geometry of the natural owl wing and which can be equipped with the aforementioned owl-specific structures. The construction of a quasi two-dimensional and a fully three-dimensional avian wing for wind tunnel testing and how it is derived from natural owl wings is described. The geometries are based on surface scans of various owl wings. First, a wing model without any owl-specific wing elements and structures (“clean wing”) being the reference case for all subsequent measurements is investigated using particle-image velocimetry (PIV) and hotwire anemometry. The main flow feature of the clean wing is a transitional separation bubble on the suction side. The size of the bubble depends on the Reynolds number and the angle of attack, whereas the location was mainly influenced by the angle of attack. Next, a second model with a modified surface is considered and its influence on the flow field is analyzed. Applying a velvet onto the suction side drastically reduces the size of this separation at moderate angles of attack and higher Reynolds numbers.

1. Introduction
In the last couple of decades the size of aircrafts and airports has rapidly grown to manage the vast number of passengers. Inevitably, this leads to an increase of starting and landing aircrafts resulting in a strong rise of the air traffic noise disturbing the direct neighborhood of airports. Therefore, it is a must to decrease the noise level and as such the noisy plight of airport neighbors. Thus, noise emission of airplanes is one major issue to airports and the design of future aircraft (Lilley, 2004), making it necessary to develop new strategies to sufficiently reduce the emission of noise by airplanes.
A major source of air traffic noise are wings and high lift devices, i.e. flaps and slats. Therefore, it will be necessary to develop new airfoils with a reduced noise emission (Hileman et al., 2007). A good example of effective noise reduction of airfoils can be found in nature. Barn owls have evolved a successful hunting strategy, which requires a very silent flight. Hunting at dawn or at night using its good vision and very acute acuesthesia to locate prey, the barn owl needs to fly silently because any kind of noise would disturb the localization or call the prey’s attention to the owl. Graham (1934) identified distinctive features that distinguish owl wings from wings of other birds, namely the velvetlike surface, the leading edge serrations, and the trailing edge fringes. In Addition, Nachtigall and Klimbingat (1985) and Biesel et al. (1985) showed the airfoil geometry of the owl wing to be different to other bird species and technical airfoils especially regarding planform and thickness distribution. The same has been evidenced by Liu et al. (2004) who reconstructed several airfoil geometries of different bird species for the purpose of numerical flow simulation.
Since the noise of a wing is produced by flow structures, e.g. vortices, it is a must to understand the aerodynamic of a wing and how it can be influenced. That is, the focus of this paper will be on the...
The influence of the velvet surface on the flow field. Itoh et al. (2006) investigated the impact of seal fur on the drag. They found the fur to reduce the drag even higher (up to 12%) and in a wider Reynolds number range than riblet surfaces. An increase of drag due to surface roughness was not observed. The impact of a soft coating on the flow field and the noise emission of a RAF-6E airfoil was investigated by Vad et al. (2006). The coating reduced the sound pressure level in the hearing range of humans, but increased it at higher and lower frequencies. However, the coating decreased the lift and increased the drag. Those results indicate that it is not just one feature but the interaction of the owl-specific features that is responsible for the silent but also highly maneuverable flight of the owl in its special habitat, i.e. trees and bushes.

The influence of surface structure and roughness has been studied by Bechert et al. (1997) for instance. Using a shear stress balance, they found the maximum drag reduction of a plate equipped with riblets or slits to be approximately 9.9%. Numerical investigations imply that the influence of riblets on the mean velocity profile to be limited to the inner region of the boundary layer.

In a joint project of the Institute of Aerodynamics and the Institute of Biology II of the RWTH Aachen University, an attempt is made, to understand the details of the aerodynamics of the owl wing and its specific features. In the future, this knowledge can be used to transfer the mechanisms reducing the noise to design a silent owl-based airfoil. That is, the findings discussed in this study focus on understanding the aerodynamics of a newly developed owl-related airfoil. As a first step, special interest is put on the airfoil geometry and the velvet-like surface in the frame of this work. All measurements were performed in the low-speed wind tunnel of the Institute of Aerodynamics. The flow field of the novel airfoil has been characterized using the particle-image velocimetry and hotwire anemometry.

In the following, the construction of a fully three-dimensional and a quasi-2D artificial wing based on the geometry of an owl wing will be discussed. Subsequently, the experimental setup is described. Next, the results are presented and analyzed in section 3, before a concise summary of the findings is given in section 4.

2. Materials and Methods

As mentioned above, the structures responsible for the reduction of the noise generated by the owl wing have been identified by Graham (1934). To understand their impact on a technical model it is necessary to build a clean wing model, which will be later equipped with those structures. That is, first the basic wing geometry has to be obtained and then, the owl-specific structures have to be rebuilt. Unfortunately, deriving the geometry from natural wings yields some serious problems. When a prepared wing is considered, the wing geometry is deformed due to drying processes of skin, tendons and feathers and due to relaxation of muscles. Additionally, the feathers result in a non-uniform surface structure and their alignment also affects the thickness, camber, and chord. All of those have a great impact on the geometry of the resulting wing model and, therefore, a strategy to deal with the deformation has to be found.

The first measurements, which will be subject to this paper, were intended to be performed on a two-dimensional reference wing, i.e., a wing without serrations and with a clean surface. That is, the low-speed flow field is only characterized by the freestream, the angle of attack, and the geometry. This wing model was to resemble an owl wing without any owl-specific structures or individual characteristics such as the velvet surface or positioning of feathers.

In the following, the procedure how the geometry of the airfoil has been inferred from a real owl wing is described. Next, the shape and the surface structure on the suction side of the airfoil are considered and in the subsequent section, the experimental setup is discussed.

2.1 Construction of an artificial owl based wing.

The Institute of Biology II considered several owls (Tyto alba pratincola) to determine the
deviation between the wings of different individuals. Although a difference in the geometry of the
wings was obvious the basic features, such as planform, thickness, and camber, were alike.
An optical surface scanner (ATOS I, GOM Optical Measuring Techniques, Braunschweig,
Germany) was used to obtain three-dimensional digital models of the wings. In preparation for the
scanning, the wings were placed in a position resembling the wing position in gliding flight. This
position was chosen because it is the favored hunting position of the owl. The positioning of the
wing was done according to photographs and videos resulting in the decision that a proper gliding
position would be a fully stretched, untwisted wing. In fact, the natural wing position is a very
unsteady state depending on the actual flight condition but only changes in a limited range, which is
why the twist is neglected. According to photographs of gliding barn owls, the leading edge of the
arm region was placed normal to the flight direction and was fixed by a metal frame during scanning.
First, the digital models of the wings were divided into several cross sections with a spatial distance
of 2 mm, each consisting of a number of points, which depended on the spanwise position of the
cross section. The final wing model was assembled of 211 single profiles, each consisting of 5000
points per upper and lower surface. The innermost cross section was placed on the border of the
scapulars. Scapulars are feathers that overlie the scapular bone and resemble a link between body
and wing. The outermost cross section was placed at approximately x/c ≈ 0.95. Since the wing tip
only consists of a few feathers, which do not overlap, it was not possible to describe this region in
terms of an airfoil.
Using the profiles extracted directly from the surface scans to construct a wing model resulted in a
shape that does not meet the requirements of a wind tunnel model. The surface was not smooth and
although the wings were fixed onto a frame they did not comply with the requirement of being not
twisted. That is, each profile was first rotated around its own leading edge to remove the wing twist.
Second, the cross sections were decomposed into a camber line, a thickness distribution, the local
chord length, and the position of the leading edge. The mathematical formulation for the camber
line and for the thickness distribution was based on algorithms given by Liu et al. (2004). The
camber line was described by a Birnbaum-Glauert function
\[ z_{(c)} = z_{(c)\text{max}} \cdot \eta(1 - \eta) \cdot \frac{1}{\eta} \sum_{n=1}^{3} S_n \cdot (2\eta - 1) \]
and the thickness distribution by
\[ z_{(t)} = z_{(t)\text{max}} \cdot \eta \sum_{n=1}^{4} A_n \cdot (\eta^{n+1} - \sqrt{\eta}) \]
where \( \eta = x/c \) is the normalized chordwise coordinate. The quantities \( S_n \) and \( A_n \) are the coefficients
of the resulting polynomials describing the considered profile. Liu et al. used an empirical estimate
by Oehme and Kitzler (1975) to correct the local chord length and account for deviations of an
individual from the mean distribution of its species. However, this approach resulted in a non-
realistic configuration and was therefore discarded. The result achieved when the leading edge and
the chord length were extracted directly from the surface scans agreed well with the natural wing.
The model constructed from the profiles described by the solution of eqs. 1 and 2 together with the
distribution of the chord length and the position of the leading edge still showed severe deficiencies.
At several positions the discrepancy of the maximum camber and the maximum thickness between
adjacent profiles was very high as exemplarily depicted in figure 1 for the maximum camber of one
scan. That is, the surface was not smooth in the spanwise direction. Even the leading edge and the
chord length did not show a smooth distribution due to feathers sticking out of the wing at the
leading edge or damaged feathers at the trailing. Using a least square fit the coefficients of the
camber line and the thickness distribution, the leading edge and the chord length were adjusted in
spanwise direction yielding a smooth wing surface.
As mentioned above, the wing geometry, especially the camber and the twist, of living and dead birds differ. Even feathers deform. To minimize the drying effects the birds were frozen directly after their death. Shortly before scanning the birds were defrosted and prepared as mentioned above. Additionally to the deformation due to drying, all active mechanisms (e.g. turning of the wrist) and some of the passive mechanisms (e.g. flexibility of skin and feathers) to control the in-flight geometry of the wing are not present if a dead wing is investigated. Both effects have a great impact on the twist and the camber line. In contrast to the camber line, Biesel et al. (1985) showed the thickness distribution to be not affected by the drying process and the ineffectiveness of in-flight control mechanisms.

An increase of the camber can also be observed in narcotized birds. This has been evidenced by Biesel et al. (1985) on pigeons (*Columbia livia var domestica*). Note, using narcotized birds the effects of drying are not taken into account. Since the owls used for scanning have been frozen directly after decease and were defrosted just before they were prepared for the scan the impact of drying is assumed much smaller than that due to the relaxation of muscles leading to a deformation similar to that of narcotized birds. Although the measurements by Biesel et al. have been performed on pigeons the results can be used to correct the camber line extracted from the owl wings. The range and the spanwise distribution of the maximum camber are similar for *Tyto alba pratincola* and *Columbia livia var domestica*. Biesel et al. measured the profile at nine spanwise locations and determined the chord length, maximum camber, location of maximum camber, maximum thickness, and location of maximum thickness of gliding and narcotized pigeons. The ratio of maximum camber of gliding and narcotized birds is presented in figure 2. These values were used to estimate a spanwise correction factor for the maximum camber, which was approximated by a 4th-order polynomial using a least square fit. The 10th value at $\xi = 1.0$ was added.

Using this distribution to correct the camber line, the geometry of the resulting model resembled the natural wing much better. The final three-dimensional model without and with corrected camber is depicted in figure 3 and 4, respectively. Note, the wing tip could not be extracted for reasons mentioned above. It was subsequently constructed using a CAD program and added to the wing model.

Additionally, a quasi-2D wing configuration based on the three-dimensional model was constructed. Assuming the owl wing to be perfectly adopted to its flight condition and to possess an elliptic lift distribution, 50% of the lift of one wing is approximately provided by the inner 40% of the wing. Therefore, this range is averaged and the resulting profile is used for the quasi-2D wing.
Figures 5 and 6 show the camber line and the thickness distribution of the quasi-2D owl based wing model. The data is juxtaposed with the camber line and the thickness distributions of an owl wing published by Liu et al. (2004). The camber line is nearly symmetric in both cases. The maximum camber of the profile measured by Liu et al. is located at $x/c = 0.47$, for the owl based profile it is located slightly downstream at $x/c = 0.50$. Unlike the camber line the thickness distribution differs somewhat. Again, the maximum of the profile of Liu et al. is located slightly upstream, i.e., $x/c_{Liu} = 0.11$ and $x/c_{owl} = 0.15$. The thickness distributions show the same features, i.e., a high maximum close to the leading edge, a strong decrease downstream of the maximum thickness, and low values in the region close to the trailing edge. Downstream of the maximum thickness, the profile investigated by Liu et al. is thinner than the novel owl based shape ($z_{t|owl} > z_{t|Liu}$ for $x/c > x/c_{max}$). The former geometry also shows a constant thickness in the region of $0.5 \leq x/c \leq 0.7$ and negative values for $x/c \geq 0.9$. In this region, the natural wing is very thin, since it consists of only one single layer of feathers. The novel thickness distribution decreases monotonically and shows no negative values at the trailing edge.

The upper and the lower surfaces of the profile are calculated by $z_{upper} = z_c + z_t$ and $z_{lower} = z_c - z_t$. The resulting profile is depicted in figure 7. Table 1 summarizes the basic geometric characteristics of the owl based quasi-2D airfoil. In the following, the quasi-2D wing with the clean surface will be denoted “wing 1a” and the wing with the velvet surface “wing 1b”.

![Fig. 3 Three-dimensional model of the wing without the correction of the distribution of the maximum camber. The z-coordinate is color coded.](image)

![Fig. 4 Three-dimensional geometry of the final wing model. The z-coordinate is color coded.](image)

![Fig. 5 Camber line of the quasi-2D wing model $z_c/z_{c(max)}$ vs. $x/c$ compared with that by Liu et al. (2004).](image)

![Fig. 6 Thickness distribution of the quasi-2D wing model $z_t/z_{t(max)}$ vs. $x/c$ compared with that by Liu et al. (2004).](image)
Fig. 7 Profile of the quasi-2D wing model.

<table>
<thead>
<tr>
<th>description</th>
<th>abbreviation</th>
<th>( z_{\text{max}} )</th>
<th>( x_{\text{zt(max)}} )</th>
<th>( z_{\text{c(max)}} )</th>
<th>( x_{\text{zc(max)}} )</th>
<th>( r_{n} )</th>
<th>( \alpha_{\text{tr}} )</th>
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<tr>
<td>chord length</td>
<td>( c )</td>
<td>0.178 m</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>span</td>
<td>( l )</td>
<td>0.5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wing area</td>
<td>( A )</td>
<td>0.089 m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>max. thickness</td>
<td>( z_{\text{t(max)}} )</td>
<td>14.77%</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>location of ( z_{\text{t(max)}} )</td>
<td>( x_{zt(max)} )</td>
<td>15.00%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>max. camber</td>
<td>( z_{\text{c(max)}} )</td>
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<tr>
<td>location of ( z_{\text{c(max)}} )</td>
<td>( x_{zc(max)} )</td>
<td>50.40%</td>
<td></td>
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<td></td>
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<tr>
<td>nose radius</td>
<td>( r_{n} )</td>
<td>11.35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>trailing edge angle</td>
<td>( \alpha_{\text{tr}} )</td>
<td>4.53%</td>
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</table>

2.2 Experimental setup.

The flow fields of the wings 1a and 1b were measured in the low speed wind tunnel of the Institute of Aerodynamics. It is a closed circuit wind tunnel with a test section possessing a cross section of 500 x 500 mm² and a length of 1200 mm. The side walls of the test section are made of plexiglass. On each side a transparent round plate exists to adjust the angle of attack. To provide optical access the top wall of the test section is made of transparent material. The measurement equipment such as probes or other sensors was installed on the bottom wall. The power unit is water-cooled to stabilize the temperature.

To obtain two-dimensional data of the velocity field, particle-image velocimetry (PIV) measurements were performed. The measurement plane was oriented in flow direction and normal to the wing surface. Only the velocity field of the suction side was recorded. A standard PIV system with a double-pulse Nd:YAG laser (New Wave Solo XT 200) and a double-shutter camera (PCO Sensi Cam) was used. A light arm connected the laser with the light sheet optics. The laser and camera were triggered at 3 Hz by a synchronizer (ILA mini PIV-Synchronizer). The pulse distance was 100 µs for \( \text{Re}_c = 40,000 \) and \( \text{Re}_c = 60,000 \), respectively, and 150 µs for \( \text{Re}_c = 20,000 \).

At an angle of attack of 3° the entire flow field of the upper side was recorded at \( \text{Re}_c = 40,000 \) and \( \text{Re}_c = 60,000 \) using up to 3000 images to determine the average velocity field and to identify separation and reattachment. Since the main interest was on the influence of Reynolds number and angle of attack on the occurring separation bubble, it was decided to limit the recorded area to range from the leading edge to approximately 65% chord length. Additionally, for all test cases the measurement plane was divided into three sections resulting in a spatial resolution of 0.4 mm between each vector, i.e., 0.0022 chord length. To determine the position of the measured field relative to the wing a calibration grid was used. The shape of this calibration grid perfectly matched the wing to achieve a high repeatability.

To verify the results of the PIV measurements, to obtain time resolved data on the velocity fluctuations, and to be able to calculate the frequency spectra hotwire measurements were performed on the suction side of the owl-based wing. Velocity profiles at 25 chordwise positions were recorded with a recording frequency of 20 kHz. For wing 1a, each profile had a length of 15 mm and was oriented normal to the chord. Because the surface of wing 1b was covered with velvet, it was not possible to place the hotwire probe as close to the surface as on wing 1a. Therefore, the profile length was reduced to 13 mm. The distance between adjacent points was 0.5 mm resulting in 30 points per velocity profile for wing 1a and 26 for wing 1b, respectively. At \( \text{Re}_c = 20,000 \) and \( \text{Re}_c = 40,000 \) a number of \( 2^{20} \) values and at \( \text{Re}_c = 60,000 \) a number of \( 2^{19} \) values were recorded. The
trailing edge was used as reference to position the hotwire probe relative to the wing. Figure 8 shows the measurement matrix for wing 1a at $\alpha = 0^\circ$.

![Figure 8 Points where the hotwire measurements were performed on the clean wing (wing 1a) at $\alpha = 0^\circ$.](image)

### 3. Discussion

The flow has been investigated using PIV to analyze the major flow phenomena. In all test cases a transitional separation bubble was present. To investigate how it is influenced by the Reynolds number and the angle of attack measurements at different Reynolds numbers ($Re_c = 20,000$, $Re_c = 40,000$, $Re_c = 60,000$) and angles of attack ($0^\circ$, $3^\circ$, $6^\circ$) were performed.

The point of separation was estimated using the PIV particle images. The contour streamline of the bubble is determined to be the line of the highest velocity gradient. Extrapolating this streamline to the surface of the wing the point of separation is determined. The data is summarized in table 4. It shows the point of separation to hardly depend on the Reynolds number, but primarily on the angle of attack and agrees well with the findings of Burgmann and Schröder (2007) on the SD7003 airfoil.

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>$Re_c = 20,000$</th>
<th>$Re_c = 40,000$</th>
<th>$Re_c = 60,000$</th>
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<tr>
<td>$0^\circ$</td>
<td>0.19</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>$3^\circ$</td>
<td>0.16</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>$6^\circ$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

![Figure 9 Averaged velocity field for a clean wing (wing 1a) at $Re_c = 40,000$ and $\alpha = 3^\circ$.](image)

The identification of the separation bubble using PIV was based on averaging 1500 instantaneous images. Figure 9 shows the average velocity field at $Re_c = 40,000$ and $\alpha = 3^\circ$. This averaged analysis suggests a clearly defined end of the separation in those cases where the bubble is closed. However, a closer look reveals that this is not the case. Reattachment does not occur at a fixed location. In fact, it is a highly unsteady and spatially oscillating process. At the downstream end of the separation bubble, the shear layer rolls up forming a vortex that eventually detaches from the bubble and moves downstream. This is illustrated in figure 10 at $Re_c = 40,000$ and $\alpha = 0^\circ$. The size of the vortex is approximately $x/c \approx 0.6$ and, thus, is consistent with the vortex size estimated with the spatial two-point correlations further below.
It goes without saying that such a flow field, which is highly susceptible to changes in the flow conditions, cannot be characteristic for the owl. Note, for the experiments mentioned above, all of the specific owl features were removed to have a clean technical reference flow (wing 1a). Therefore, the owl-specific structures of the owl wing must have a considerable influence on the development of the flow field on the wing and hence on the flight performance of the owl. Applying those structures to this wing, it is possible to investigate their influence in detail. In a first step the special surface structure of the owl wing has been investigated. For that reason, the suction side of the wing was covered with velvet (wing 1b). The velvet was chosen to match the geometric characteristics of the real surface structure of the owl wing, i.e., the length and the density of the hairs (Bachmann et al., 2007). Figure 11 shows a comparison of the natural and the artificial surface structure. The material properties were only checked manually. That is, the Youngs-modulus has not been investigated but the feel of the natural and the artificial surface is alike.

PIV measurements were performed to analyze the impact of the velvet surface on the overall flow field. The comparison of the velocity distributions of wing 1a and wing 1b is shown in figures 12 and 13. The slight discontinuities in figures 12 and 13 are due to the decomposition of the measurement plane into three sections to enhance the spatial resolution. Before each measurement the calibration grid was placed on the wing to determine the position of the measurement plane relative to the wing and using the chord based Reynolds number $Re_c$ and the temperature the corresponding freestream velocity was calculated. Minor errors in placing the calibration grid or in calculating the freestream velocity caused the observed discontinuities.

The velocity distributions illustrated in figures 12 and 13 evidence the influence of the surface structure on the separation bubble. The effect seems to be a combination of an increased roughness and something similar to a riblet structure due to the alignment of the hairs (Itoh et al., 2006). Both, the roughness and the riblets, have a significant impact on the aerodynamic performance since they influence the separation, consequently the transition onset, and thus, the reattachment (Roberts and Yaras, 2006). For all flow conditions shown in figures 12 and 13 the point of separation moves upstream at increasing angle of attack on wing 1a as well as on wing 1b. At $Re_c = 20,000$ and $\alpha = 6^\circ$ no influence of the velvet on the reattachment can be observed. That is, the perturbations excited by the velvet surface are not strong enough to increase the momentum exchange in the near-wall layers such that separation can be avoided or the flow can be forced to reattach. At higher Reynolds numbers, i.e., $Re_c = 40,000$, the influence does depend on the angle of attack. At $\alpha = 6^\circ$ the flow over

![Fig. 10 Instantaneous PIV image of vortices at the end of the separation bubble at $Re_c = 40,000$ and $\alpha = 0^\circ$. The color defines the distribution of the normal velocity component.](image)

![Fig. 11 Surface structure of the natural owl wing (left) and the applied velvet (right). The black bar at the bottom represents a length of 400 µm.](image)
the suction side of the clean wing completely separates. The PIV image in figure 13(c) also shows the flow over the velvet surface to be detached. At lower angles of attack, however, the size of the separation bubble decreases due to the velvet surface. That is the separation bubbles at \( \text{Re}_c = 40,000 \) and \( \alpha = 0^\circ \) and \( 3^\circ \) in figures 13(a), 13(b) are smaller than in figures 12(a), 12(b).

![PIV Image](image)

**Fig. 12** Averaged velocity fields for a clean wing (wing 1a) at \( \text{Re}_c = 40,000 \) and \( \alpha = 0^\circ, 3^\circ, \) and \( 6^\circ \).

**Fig. 13** Averaged velocity fields for a velvet wing (wing 1b) at \( \text{Re}_c = 40,000 \) and \( \alpha = 0^\circ, 3^\circ, \) and \( 6^\circ \).

The reattachment of the flow occurs due to laminar turbulent transition, which is excited by the inflection in the velocity distribution in the separated flow regime. To identify the transition region the \( u'v' \)-correlation of the Reynolds shear stress tensor is analyzed. The process of separation and reattachment is dominated by vortex structures which form in the separation bubble, drift downstream, and finally detach from the bubble effecting the location of the transition onset. Therefore, it is not one definite position where transition sets in but rather a zone in freestream direction where an increase of the Reynolds shear stress can be observed as shown by Burgmann et al. (2007) on a SD7003 airfoil.

An increase of the Reynolds shear stresses is also observed in the flow field over the owl based wing independent of the clean or the velvet surface. The transition onset is determined as described by Burgmann and Schröder (2007) and McAuliff and Yaras (2005). The distributions of the normalized Reynolds shear stresses are shown in figures 14 for wing 1a and 15 for wing 1b, respectively. It is obvious that the increase in the Reynolds shear stresses occurs closer to the leading edge for wing 1b.

The rise in the values of the maximum Reynolds shear stress occurs slowly. At higher angles of attack as well as at higher Reynolds numbers the beginning of the increase moves further upstream, which corresponds with the shift of the separation point. The more upstream occurring transition due to an increased Reynolds number leads to an earlier reattachment. That is, unlike the separation point, which is hardly influenced by the Reynolds number, the transition onset and thus the reattachment depends on the Reynolds number.
Based on the PIV data, the spatial two-points correlations are calculated. As pointed out above for the average velocity images, the images of the spatial two-point correlations show the same discontinuities. Since the two-point correlations are not computed across the borders of the sections of the measurement plane the values differ and the structures possess a pronounced alteration. Using spatial two-point correlations it is possible to estimate the size of the vortices and the location where they emanate. The distribution of the local maxima and minima indicates the average streamwise extent of a shed vortex and the distance between two consecutive vortices (Kim et al., 1987). Furthermore, the regions of strong correlation also describe where the vortices arise and how their size develops downstream. The contours of the spatial two-point correlation of the normal velocity component are shown in figure 16 for $Re_c = 40,000$ and $\alpha = 0^\circ$ for wing 1a and wing 1b, respectively. The correlations reveal significant differences in the location where the correlations are highest and the size of the structures.

Cal et al. (2007) investigated the development of a boundary layer over a rough surface under a favorable pressure gradient. They stated the surface roughness to destroy the near-wall coherent structures. This implies that the size of those flow structures, which eventually dissipate downstream, would be rather small, or at least smaller than that for the clean surface. These findings are corroborated by comparing the structures of the spatial two-point correlations of wing 1a and wing 1b. The spatial two-point correlation of the normal velocity component for wing 1a in figure 16(a) indicates the location from where vortices start to shed to be approximately located at $x/c \approx 0.31$. The distance between the maximum and the minimum, which approximates the radius of a vortex, is approx. 0.03 c. Consequently, the size of a vortex, i.e., the distance between two adjacent minima is approx. 0.06 c, which agrees well with the size of the vortex in the...
instantaneous PIV image (figure 10). The velvet surface (wing 1b) shifts the point, where the vortices start to shed, closer to the leading edge $x/c \approx 0.13$ and diminishes the radius of the vortices to roughly $0.02c$ and the distance between them to approximately $0.04c$.

Note, the smaller vortex size and the occurrence of vortices further upstream for wing 1b substantiates the above statement visualized in figures 14 and 15 that changing the surface structure moves the transition onset further upstream and decreases the size of the separation bubble.

To further substantiate the results of the PIV measurements, hotwire measurements were performed. The mean velocity profiles are determined at 25 chordwise positions. Additionally, the velocity fluctuations can be calculated and it will be possible to use the data of the hotwire measurements to calculate the frequency spectra. The mean velocity profiles of wing 1a and wing 1b are presented in figure 17. It shows the size of the separation bubble to be reduced by the velvet surface, which agrees well with the results of the PIV measurements. Further investigations of the velocity fluctuation and the frequency spectra have to be done to describe the influence of the velvet surface in more detail.

![Fig. 17 Mean velocity distribution of the owl-based wing with and without velvet surface measured with hotwire anemometry.](image)

4. Conclusion and Outlook

The wings of several barn owls have been investigated. Using three-dimensional surface scans an artificial wing for wind tunnel tests has been constructed. The surface scans have been divided into approximately 200 cross sections. Mathematical algorithms based on a Birnbaum-Glauert distribution have been used to extract the camber line and the thickness distribution. Together with the local chord length and the position of the leading edge these profiles have been reassembled to a three-dimensional artificial wing with a clean surface.

The resulting shape showed the characteristics which are special for owls. The owl wing’s planform is rather elliptical having an area which exceeds by far the area of similar sized birds (e.g. pigeons). In the inner half of the wing the thickness is mainly concentrated close to the leading edge ($x/c \leq 0.25$). Downstream of the location of maximum thickness, the thickness decreases drastically resulting in a very thin trailing edge of the wing. The camber line is symmetrical and the position of the maximum camber is located at approximately $x/c = 0.50$. Consisting of only one layer of feathers with small overlap and almost no camber, the outer half of the wing resembles rather a flat plate.

The three-dimensional model has been used to derive a quasi-2D wing model by averaging a certain interval of the span. Assuming the owl wing to be perfectly adapted to its flight conditions and to possess an elliptical lift distribution, the chosen interval ($0.0 \leq x/c \leq 0.4$) would provide half of the total lift of a single wing.

Particle-image velocimetry and hotwire measurements have been used to record and analyze the flow field of the novel owl based quasi-2D airfoil. The existence of the separation bubble and its dependence on the Reynolds number and the angle of attack was evidenced by the particle-image velocimetry and hotwire anemometry.

Next, the wing has been equipped with a velvet surface resembling the velvety soft surface of an owl wing to investigate its influence on the flow field. At higher Reynolds numbers and at moderate
angles of attack, the size of the separation bubble has been reduced significantly. It is assumed that the impact of the velvet surface is a combination of an increased surface roughness and some kind of riblet structure due to the alignment of the hairs.

Since the reattachment is forced by the transition from laminar to turbulent, a decrease in the size of the separation bubble and, hence, a reattachment further upstream, corresponds to a transition onset further upstream. It is obvious that the velvet surface shifts the point of transition onset upstream in all test cases.

The influence of the velvet surface is also evident in the $v^$v$^$-correlations. In all test cases, the size of the vortices and their distance are diminished by the velvet surface. At the same time, the point where the vortices develop moves further upstream.

The experiments for the velvet surface emphasize the special structures of the owl wing, i.e. the velvet surface and the leading edge serrations, to be essential for the flow field. An understanding of the aerodynamics of the owl wing and how it is influenced by the different structures is necessary to come up with ideas how to transfer those effects to the much higher Reynolds number range of aircraft and how those mechanisms can be used to design a silent airfoil. Further experiments will be conducted for the fully three-dimensional wing to investigate the impact of the serrations and of the material properties, i.e., Youngs modulus, of the surface structure on the three-dimensional flow field.

5. References


Burgmann S, Schröder W (2007) Investigation of Kelvin-Helmholtz induced separation bubble flapping via time-resolved and scanning PIV measurements. Submitted to Experiment in Fluids

Burgmann S, Dannemann J, Schröder W (2007) Time-resolved and volumetric PIV measurements of a transitional separation bubble on an SD7003 airfoil. Experiment in Fluids published online


Oehme H, Kitzler U (1975) On the geometry of the avian wing (studies on the biophysics and physiology of avian flight II). NASA-TT-F-16901
