PIV measurements comparing natural and model owl wings

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Abstract Concerning the geometry and plumage the wing of the barn owl differs considerably from wings of birds which possess a similar weight and size. Due to the special geometric features like an almost elliptic planform, a distinct nose region, and a location of maximum thickness at low chordwise positions in combination with unique plumage adaptations, i.e., the leading-edge serrations, the velvet-like surface structure, and the trailing-edge fringes, the owl is able to perform stable and highly maneuverable gliding flight at low velocities. Additionally, the natural owl wing possesses a high level of flexibility and is able to adapt to the current flight condition. Thus, the combination of the owl-specific geometry and plumage with the flexibility of the wing structure creates a highly complex flow field which is compared to the flow field around a rigid wing model with only one unique feature, e.g., the velvet surface structure, applied to evaluate the influence of the intricate interaction mechanisms of the natural wing.

High-speed particle-image (PIV) measurements are performed on wing models which possess the basic special geometric characteristics of the barn owl wing. Two models are additionally equipped with artificial textiles which are selected based on the geometric and material similarity to the natural structure. To be able to differentiate between the influence of the wing geometry and the surface structures the results are compared to PIV measurements executed on a prepared natural owl wing which additionally incorporates the leading-edge serrations and the trailing-edge fringes. Measurements were performed in a range of angles of attack $0^\circ < \alpha < 6^\circ$ and Reynolds numbers $40,000 < Re_c < 120,000$ based on the chord length.

A laminar separation bubble is the dominant flow phenomenon on the wing’s suction side for the technical wing models. Also, a strong influence of the surface structures on the flow field is evident for both velvet structures that are applied to the models. Unlike the flow field around the models, the natural wing does not show any flow separation. Additionally, a strong dependence of the wing geometry and the structural deformation on the Reynolds number is found for the natural wing in contrast to the rigid wing models. Investigations of the flow on the lower side of the natural wing indicate a considerable influence of the pressure side on the entire flow field around the natural wing as well as the wing’s deflection and deformation, disproving the findings the separation bubble to be the dominant flow feature found for the wing models.

Keywords Three-dimensional airfoil aerodynamics, Natural owl wing, Velvet surface structures, High-speed PIV

1. Introduction

Unlike many other bird species, the barn owl shows how flight noise can be reduced very effectively. Since the barn owl hunts its prey at night, visual information is limited and the owl has to rely on acoustic information to detect and localize potential prey. Thus, any noise emitted by the owl itself has to be avoided during hunting to be able to detect the prey and not to be recognized by the prey. To reduce noise emission to a minimum, owls have an unique wing geometry and several surface- and edge- modifications. One of the key features of the owl's silent flight is the low flight velocity during hunting. According to Mebs and Scherzinger [14] the owl approaches its prey in gliding flight at relatively low speeds of $2.5\ m/s$ to $7.5\ m/s$, although unfavorable flow phenomena such as flow separation are likely to occur in this low Reynolds number regime, i.e., $30,000 < Re_c < 100,000$ based on a chord length of approximately $180\ mm$. These phenomena are accompanied by undesired side effects, e.g., a reduction of lift, a rise of drag, and pressure fluctuations which lead to alternating pitching moments [13]. The understanding of the mechanisms which enable the owl to fly at such low velocities in conjunction with the reduced noise level does provide potential considering the aerodynamics of so-called micro air vehicles (MAVs). The wings of barn owls are large in comparison to birds of similar weight. Thus, the wing loading is reduced
due to the larger wing area. Additionally, the wing possesses a nearly elliptical planform and other special geometric features such as a strong camber and a drip nose geometry which indicate that the owl wing is mainly designed for low-speed gliding flight. The findings of Klän et al. [8] suggest that this geometry of the wing leads to an extended suction area in the pressure distribution. Therefore, a separation bubble, i.e., a region of local flow separation, is likely to occur at the suction side. Also, the aerodynamic forces, i.e., lift and drag and, thus, the aerodynamic performance are determined by the pressure distribution. To perform a highly maneuverable low-speed gliding flight, the owl must be able to reduce and control this separated flow. Therefore, in addition to the special wing geometry, the owl possesses adaptations on its wing and plumage which might influence the flow field allowing low-speed silent gliding flight. Also, the natural owl wing possesses a high flexibility, enabling the owl to adapt its geometric wing shape to the flow condition such as angle of attack and Reynolds number, i.e., flight velocity.

All natural wings are formed by feathers which are attached to the skeletal elements of the forelimb and its integument. The plumage of the owl consists of the major flight feathers, the so-called remiges and the coverts. The remiges can be further divided into the primaries, which are attached to the hand bones and the secondaries that are supported by the ulna. The anatomy of a barn owl wing is presented in fig. 1.

In comparison to other bird species of comparable weight and size, the wings of owls possess a specific camber and thickness distribution [17]. The wing can be divided into a proximal and a distal part by anatomical and geometric features. According to Bachmann et al. [2] these two parts differ from another since the proximal part possesses a high camber in combination with a thick leading edge. This thickness is formed by skeletal elements, muscles, and several rows of coverts. Unlike the thick leading edge, the trailing edge is build up only by single remiges resulting in an extremely thin structure. The distal part of the wing is
formed by overlapping primaries and can be compared to a slightly cambered plate. One of the prominent characteristic of the owl wing, namely the large wing size, is realized by overlapping remiges with high proportions which mechanically stabilize the surface of the wing.

Apart from the wing geometry, Graham [7] identified leading-edge serrations, trailing-edge fringes, and a velvet-like surfaces structure on the suction side of the wing to be unique to owl species. A brief description of these owl-specific adaptations is given in the following.

The comb-like serrated leading edge of the distal wing is determined by the 10th primary remex as shown in fig. 2.

![Fig. 2: Serrations at the outer vane of a barn owl's 10th primary in different magnifications [3]](image)

![Fig. 3: Fringes at the inner vane of a barn owl's remex in different magnification [4]](image)

Note that only the parts that are directly subjected to the flow are serrated. The serrations are formed by single barb endings that separate distally and bend upwards. The length of the hook and bow radiates decreases towards the tip of the serration, supporting the serration's tapering. Distance and length vary depending on the size of the bird and the position of the serrations on the wing. According to Bachmann and Wagner [3] the spacing between the serrations found in North American barn owls is approximately $600 \mu m$, whereas their length varies between $1.8 mm$ and $2.7 mm$.

Another prominent feature of the barn owl wing are the fringes which are found at the inner vanes of all remiges. These fringes are displayed in fig. 3 in different magnifications. Here, barb endings separate due to a loss of hooklets of the hook radiates. Unlike hook and bow radiates that align with the barb shaft to support the formation of fringes, barbs remain separated due to small barbicles at the pennula of the hook radiates. During flight, fringes occur at the trailing edge of the extended wing as well as at the trailing edge of each remex [7, 1].
The velvet-like structure which is characteristic for the upper side of the natural owl wing is caused by the elongated pennula. Although this structure is found on the inner and outer vane of each feather, there are significant differences in the development of the structure. The parts of the feathers which are subjected to the flow during flight possess a shorter pennula compared to the areas covered by other feathers. In this region, the structure has a brush-like shape and the tips of the pennula point into the flow. Here, the pennula are mostly directed against the air flow [1]. The velvety surface structure is presented in fig. 4 in different magnifications.

Several studies performed by Klän et al. [8, 9] focused on the effect of artificial velvet-like surface structures on the near-wall flow field. These structures were derived from the natural surface of the owl wing and were applied on three-dimensional wing models the geometry of which was based on that of the owl wing. It was found that the velvet surfaces directly influenced the size of the laminar separation bubble caused by the strong adverse pressure gradient. The location of the laminar-to-turbulent transition and the point of reattachment were shifted upstream, hence separation on the wing models was decreased or even suppressed depending on the Reynolds number and angle of attack.

To further investigate the segregated influence of the surface structures on the near-wall flow field, additional high speed particle-image velocimetry (PIV) measurements were performed on wing models equipped with two different artificial structures. In contrast to the technical wing models, a natural wing not only contains the aforementioned owl-like geometry and the owl-specific adaptations of the plumage, but also possesses a high level of flexibility, i.e., the wing is able to interact with the surrounding flow field, leading to a deformation and movement of the wing. Also, the structure can be considered porous, allowing air to pass from the pressure to the suction side. Thus, it can be assumed that the flow field around the natural wing might be more complex compared to the flow field around the wing models.

Lentinik et al. [10] experimentally investigated the influence of wing morphology on the aerodynamic performance of common swift (Apus apus). For the experiments pairs of swift wings were frozen, freeze-dried, and glued together to form a wing shape which was manually extended to reproduce the wing shape during gliding flight at five different sweep angles. These wings were mounted onto a specially designed balance system and positioned in a wind tunnel. The authors found that although extended wings provide the best glide performance, high sweep improves aerodynamic performance at higher-than-optimal speeds. They concluded that the wide range of tasks of bird living an aerial life style may conflict with the goal of...
maximum aerodynamic performance. Withers [22] investigated nine bird species with various morphometric parameters concerning their aerodynamic performance. Measurements were performed on fixed natural wings, prepared in a position which resembles gliding flight. He found that bird wings, which generally operate at lower Reynolds numbers than common airfoil, possess high minimum drag coefficients in the range between 0.03 to 0.13, which in combination with low maximum lift coefficients of 0.8 to 1.2 result in a low overall aerodynamic performance, i.e., lift-to-drag ratios of 3 to 17 and airfoil efficiency factors of 0.3 to 0.8 in contrast to 0.9 to 0.95 for conventional airfoils. Also, Withers assumes that bird wings possess a higher drag coefficient compared airfoils at equivalent Reynolds number due to the natural surface roughness of bird wings, wing twist, and the tendency of individual feathers to flutter and, hence increase the drag.

In a more current study March et al. [12] experimentally investigated the aerodynamic forces on a fixed wing of a great horned owl (Bubo virginianus) in wind-tunnel experiments. They found the wing to be highly aeroelastic, influencing the aerodynamic forces acting on the wing. They assumed that due to the aeroelasticity, the bird is able to adapt the wing shape to the various flight regimes, i.e., if the bird's speed increases beyond the optimum value, the wing will automatically align to the drag-minimizing configuration.

The goal of this study is to analyze the flow field around a real owl wing that possesses all the aforementioned special adaptations and to compare it to the flow around a technical wing that possesses the geometric shape of the owl wing and that is equipped with only of the features, namely the velvet-like surface. Hence, the objective is to investigate, in how far the combination of flexibility, leading-edge serrations, trailing-edge fringes, and velvet-like surface influences the flow field around the wing and in how far this flow field differs from that of the rigid wing model with only one of the owl-specific adaptations.

For this purpose high-speed PIV measurements are performed for the technical and the natural wing since this technique offers the possibility to analyze the spatial and temporal development of the turbulent flow in detail. Furthermore, the PIV images can also be used to measure the deflection and thus the reaction of the wing on the flow.

In addition to the visualization of the velocity distribution, the chordwise distribution of the time-averaged maximum Reynolds shear stresses is used to detect the location of transition onset and hence draw conclusions on the state of flow on the suction side of the wing. Also, spatial two-point correlations of the wall-normal velocity fluctuations w' were used to analyze the flow phenomena around the wing. Since the natural wing possesses a high level of flexibility due to the structural build-up of bones and feathers, the natural wing is able to interact with the surrounding flow field in contrast to the rigid wing models. Hence, since the natural wing exposed to the airflow is deformed, its contour and thus its curvature is detected via the laser light reflection line and analyzed as a function of the Reynolds number. Additionally, the measurements allow a detailed tracking of the trailing edge, i.e., the vertical and horizontal location of the downstream end of the wing. Thus, the amplitude and the frequency of the wing's motion can be measured and directly correlated to the flow field.

The manuscript is structured as follows. First, the experimental setups for the PIV measurements of the wing models (sec. 2.1) and the natural wing (sec. 2.2) are introduced. The results of the PIV measurements are divided into three parts. In the first section (sec. 3.1), the flow field around the wing models and the natural wing are thoroughly investigated and compared. In the following sections the contour line (sec. 3.2) and the movement of the trailing edge (3.3) are described for the natural wing. To identify the origin for the deflection, the flow field on the lower side of the natural wing is investigated and connected to the findings of the trailing-edge tracking (3.4). Finally, the results of the flow field and contour analysis are summarized in the conclusion.

2. Experimental setup

All experiments were performed at a temperature-compensated low-speed wind tunnel with a rectangular shape with a cross section of 800 mm×800 mm. To investigate the flow field around wing models equipped with artificial surfaces structures on the one hand and natural wings on the other hand, two sets of measurements were performed. The experimental investigations of the three-dimensional wing models were performed in an open test section, whereas the natural wing was investigated in a closed test section. For both configurations, the flow on the ground plate was tripped by a 0.5 mm wire to ensure a turbulent boundary layer. As stated by Mueller [15] and Mueller et al. [16], the flow around a wing model at low Reynolds number might encounter hysteresis effects, resulting in a significant alteration of the flow field.
This even holds for small changes of the angle of attack. To avoid this 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 configuration.

2.1 PIV measurements of the three-dimensional wing models

The three-dimensional wing models are based on the geometry of a barn owl wing. Its shape is characterized by strong camber and a drip nose geometry. A more detailed description of the extraction of the wing shape from natural wings and the geometry of the wing models can be found in Klän et al. [8].

The three-dimensional wing models possess a half span of \( b/2 = 431 \text{ mm} \). Hence, the projected distance between the tip of the wing model and the upper edge of the wind tunnel nozzle was 369 mm, resulting in a negligible influence of the nozzle contour on the flow field. The wind tunnel models were positioned 400 mm downstream of the nozzle exit.

Previous investigations of Liu et al. [11] have shown that the lift distribution in the spanwise direction of an owl wing is almost elliptic. The inner 40% of the span of the wing model provide approximately 50% of the total lift force of the wing force. Therefore, the chord length that is used to calculate the Reynolds number is the mean chord length of the aforementioned region of the wing model, although the chord length varies with the spanwise position, i.e., the mean chord length is \( c = 178 \text{ mm} \). Reynolds numbers of \( Re_c = 40,000, 60,000, \) and \( 120,000 \) corresponding to freestream velocities of \( u_\infty \approx 3.5, 5.3, \) and \( 10.5 \text{ m/s} \) were measured.

Three angles of attack, namely \( \alpha = 0^\circ, 3^\circ, \) and \( 6^\circ \) were investigated since these angles are assumed to be part of the owl's flight envelope [21]. Also, four spanwise positions close to the wing root, i.e., \( 2y/b = 0.12, 0.20, 0.25, \) and \( 0.3 \) were selected since at this spanwise position the phenomenon of a laminar separation bubble found by Klän et al. [8] was most likely to occur. The investigation of various spanwise positions also allows the analysis of the influence of the three-dimensionality of the wing model. Figure 5 shows a picture of the wing with the measurement planes.

Time-resolved 2D-2C particle-image velocimetry measurements were performed to investigate the flow field of the technical wing models. As light source a Quantronix Darwin Duo high-speed laser with a maximum laser power of 40 W at a reference frequency of 3000 Hz was used. The PIV images were recorded via a Photron SA3 CMOS high-speed camera with a maximum resolution of 1024 px × 1024 px at the measuring frequencies of 2000 Hz for the measurements performed at \( Re_c = 40,000, 60,000, \) and 4000 Hz at \( Re_c = 120,000, \) respectively. A Nikon optical lens with a focal length of 50 mm and a minimum f-number of 1.8 was used for the experiments. A high-speed synchronizer of the ILA GmbH was used to trigger the
camera and the laser. For each configuration, 1000 images were recorded to ensure converging statistic of the unstable flow field. As seeding particles Di-Ethyl-Hexyl-Sebacat (DEHS) droplets with a mean diameter of $d_p \approx 1 - 2 \mu m$ were used. The particles were equally distributed in the flow via a Laskin-nozzle seeder. The post-processing was done using the PivTec / ILA GmbH software PivView. The size of the final interrogation window was $24 \times 16$ with an overlap of $12 \times 8$ in the horizontal direction and an overlap of $8 \times 8$ in the vertical direction, leading to a horizontal vector spacing of $\Delta x = 3.02$ or $\Delta x = 0.0117$ and a vertical vector spacing of $\Delta y = 1.56$ or $\Delta y = 0.0088$. A schematic of the experimental setup is given in fig. 6.

![Fig. 6 Schematic of the PIV measurement setup of the three dimensional wing models.](image)

200 hairs per $mm^2$ with a mean diameter of $d = 6 \mu m$ and the tendency to stick together and form bundles characterize the surface of the natural wing. Since it is hard to mimic this behavior two artificial surfaces were selected to imitate the natural surface. To investigate the impact of the surface structure on the flow field, the three-dimensional wing models are equipped with these artificial textiles.

<table>
<thead>
<tr>
<th>Tab. 1. Properties of the natural surface of the wing and the two artificial surface structures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
</tr>
<tr>
<td>[n/mm²]</td>
</tr>
<tr>
<td>natural</td>
</tr>
<tr>
<td>velvet 1</td>
</tr>
<tr>
<td>velvet 2</td>
</tr>
</tbody>
</table>

‘Velvet 1’, the first artificial surface, was selected to imitate the natural surface concerning the length, density, and softness of the hairs. Velvet 1 does not possess a preferred filament direction and after horizontal deflection, the hairs return to their vertical orientation within $10 \, ms$. The second velvet structure, in the following referred to as ‘velvet 2’, is build up of longer filaments that are softer than those of the natural structure or velvet 1. Also, this textile possesses a preferred orientation of the filaments. It was positioned to be aligned with the mean freestream direction. In contrast to velvet 1, the filaments of velvet 2 tend to stick to the surface when they are horizontally deflected in the preferred direction of the filaments, whereas they
return to their vertical orientation within 10 ms when they are deflected in the opposite direction. Table 1 summarizes the properties of the three different surface structures.

The combination of the presented parameters, i.e., surface structure, spanwise position, angle of attack, and Reynolds number, leads to 108 parameter sets that were investigated. A complete overview of all measurement configurations is given in tab. 2.

<table>
<thead>
<tr>
<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>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>

2.2 PIV measurements of the natural owl wing

The measurements on the natural owl wing were performed in a closed test section of the same wind tunnel. The reason for the closed test section was the use of Expancel microspheres as seeding particles. The natural wing possesses an approximate half span of \( b/2 = 420 \text{ mm} \). Additionally, the mounting of the natural wing required a height of approximately 60 mm. Thus, the projected distance between the upper edge of the wind tunnel nozzle and the wing tip was 320 mm. Since the boundary layer on the side walls of the tunnel was approximately in the range of 50 mm at the measurement location effects from the test section walls can be neglected. The test section possesses a cross section of 800 mm × 800 mm and a length of 2200 mm. The maximum blockage of the wind tunnel was 2.6% at an angle of attack of \( \alpha = 6^\circ \). The walls of the test section were adapted in such a way that the optical access was possible from all camera positions. The position of the measurements was located 400 mm downstream of the nozzle exit.

Similar to the measurements performed on the wing models, a mean chord length of \( c = 178 \text{ mm} \) was used as reference length for the calculation of the Reynolds number. The actual measured chord length at the spanwise location of \( 2y/b = 0.3 \) was \( c = 174 \text{ mm} \). The same Reynolds numbers, i.e., \( Re_c = 40,000, 60,000, \) and \( 120,000, \) and the same angles of attack, namely \( \alpha = 0^\circ, 3^\circ, \) and \( 6^\circ \) were measured. Unlike the experiments performed on the wing models, only three spanwise positions at \( 2y/b = 0.3, 0.5, 0.7 \) were selected. These spanwise positions were used to capture the three-dimensionality of the flow field and the structural movement of the overall wing. An overview on the measured parameters is given in tab. 3.

<table>
<thead>
<tr>
<th>Spanwise position 2y/b [-]</th>
<th>Angle of attack α [°]</th>
<th>Reynolds number Re_c [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0</td>
<td>40,000</td>
</tr>
<tr>
<td>0.5</td>
<td>3</td>
<td>60,000</td>
</tr>
<tr>
<td>0.7</td>
<td>6</td>
<td>120,000</td>
</tr>
</tbody>
</table>
2D-3C high-speed PIV measurements were performed on the natural wing. The experimental setup for the measurements of the upper surface includes a Quantronix Darwin Due high-speed laser with a maximum laser power of 100 W at a reference frequency of 3000 Hz and two Photron SA5 CMOS high-speed cameras which possess a maximum resolution of $1024 \times 1024$ px. The schematic of the setup is presented in fig 7. Similar measurements were also performed on the lower side simultaneously. For the measurements of the lower surface two Photron SA3 CMOS high-speed cameras with a maximum resolution of $1024 \times 1024$ px were used. The measurement frequency was $4000$ Hz for all Reynolds numbers investigated. Four Zeiss optical lenses with a minimum f-number of 2.0 and a focal length of $100$ mm were selected. To guarantee converging statistics of the unstable flow field and also the possibility to detect low frequency oscillation in the flow field or the structural behavior, 4000 images were recorded for each configuration.

To detect the contour line and the movement of the wing, one measurement campaign was performed with bandpass interference filters positioned in front of the optical lenses. The wavelengths of the filters was selected to allow the passing of light in a wavelength range of $527 \text{ nm} \leq \lambda \leq 537 \text{ nm}$, i.e., the laser light of the high-speed laser reflected by the tracer particles, which possesses a wave length of $\lambda = 527$ nm, was able to pass the filters with only a relatively small reduction of intensity. On the other hand, the light reflected by the wing's surface was scattered at a wave length of $\lambda = 565$ nm due to the shift in wave length caused by the coloring of the surface with Rhodamine B as described below. Therefore, the reflections caused by the curved wing surface were reduced, allowing a more accurate detection of the wing's contour and movement. The reason to use Rhodamine B for the coloring of the wing is given later in this section.
As mentioned above, the setup was designed to measure the upper and lower surface of the wing simultaneously. Thus, the flow field on both sides of the wing has to be illuminated at the same time. To guarantee a comparable strength of the laser beams, the beam of the aforementioned Darwin Duo high-speed laser was split into two beams. The corresponding light path is visualized in fig. 8. The light sheet for the measurements of the upper surfaces is marked by the letter ‘u’, the light sheet for the lower side with ‘l’, respectively. The laser beam is released by the laser head, which is positioned in the center plane underneath the test section. The beam is sent through a focusing optic, build up of two cylindrical lenses of different focal lengths. The flexible adjustment of the relative position of the lenses allows to focus the laser beam at the measurement plane. The beam is sent through a beam splitter, i.e., a half-reflecting mirror, which horizontally reflects the relevant half of the laser beam by 90° in the positive z-direction, i.e., in the direction of the side wall of the test section. Behind the beam splitter when a position behind the side wall of the test section is reached, the beam is reflected by the mirror $M_{1u}$ in the horizontal plane once more by 90° this time in the negative x-direction. When reaching mirror $M_{2u}$, the beam is reflected vertically by 90°, i.e., in the positive y-direction. At the height of the measurement plane, another mirror denoted as $M_{3u}$ is used to horizontally reflect the beam in the direction of the wing. The beam reaches the wing at an approximate angle of 45° to ensure a sufficient light scattering behavior of the seeding particles. To spread the light sheet in the measurement plane, two cylindrical lenses were used. These lenses were selected to ensure a sufficiently thin and at the same time wide light sheet in the measurement plane. This light sheet optics is labeled $LS_u$. The path of the lower side is guided analogously.

The flow was seeded with Expancel Microspheres 461 DET 40 d25 (MS). These particles possess a density of $25\text{ kg/m}^3$ and a mean diameter of $d_p \approx 40\mu m$, i.e., they are significantly larger than the DEHS droplet used for PIV measurements in general and for the measurements of the wing models in particular. The microspheres were used as seeding particles due to the high sensitivity of the natural owl wings’ structure to laser light. Experiments performed on another owl wing revealed the tendency of the keratin in the feathers to melt when high laser power or long measurement times were applied. Thus, the laser power used in the experiments was limited by the structural integrity of the wing’s surface. Therefore, seeding particles with a better light scattering behavior than DEHS were required to ensure a sufficient light intensity.

According to van Overbrüggen et al. [18] the relaxation time $\tau_s$ of the Microspheres can be calculated to $\tau_s = 119.35\mu s$, whereas DEHS possesses a relaxation time of $\tau_s = 3\mu s$. The Stokes number $S_k$ reads

$$S_k = \frac{\tau_s}{t_f}$$

where $u_f$ represents the characteristic flow velocity and $l_f$ a characteristic length scale of the flow. Tropea et al. [19] state that for values of $S_k$ below 0.1 an acceptable flow tracing accuracy with errors below 1% is reached. Previous measurements performed on the three-dimensional wing models showed that the integral length scale is in the range of approximately 8 mm at a flow velocity of about 5 m/s [20]. Thus, the corresponding Stokes number is $S_k = 0.08$. For higher flow velocities and/or smaller integral length scales, the Stokes number and the corresponding error in the flow tracing accuracy increases. At the highest Reynolds number investigated, i.e., $Re_c = 120,000$, the current measurements show dominant flow structures with a characteristic length of approximately 18 mm, leading to a Stokes number of $S_k = 0.07$. Thus, a sufficient flow tracing accuracy can be assumed for the investigated flow cases.

Additionally, van Overbrüggen et al. [18] performed two-component PIV measurements to compare the flow-following behavior of DEHS droplets with microspheres. The acquired velocity fields were used to calculate the corresponding energy spectra at a given location. The spectrum of the inertial subrange is captured by both kinds of seeding particles. Also, the energy spectra show a good agreement in the range of the large scales, whereas in the range of the smaller length scales, i.e., the Taylor scales, the microspheres are not capable to represent the flow correctly. Therefore, this drawback of the reduced flow-following capability has to be taken into account for all measurements performed on the natural owl wing.

To avoid the bright reflections of the laser light on the wing, which are caused by the color and curvature of the feathers, the fluorescence dye Rhodamine B was used to color the upper and lower surface of the natural wing. Especially the lower side of the wing suffers from reflections due to its white color. Rhodamine B was selected because additionally to the coloring of the wing surface, microscopic investigations that the surfaces structure of the natural wing was not affected by the application of the dye.
As for the measurements of the wing model, the post-processing of the PivTec / ILA GmbH software PivView was used. The final interrogation window size was 24 px $\times$ 24 px with an overlap of 6 px, i.e. 75%, resulting in a vector spacing of $\Delta x_v = 2.27$ mm or $\Delta x_v = 0.013c$.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Spanwise position $2y/b$ [-]</th>
<th>Angle of attack $\alpha$ [$^\circ$]</th>
<th>Reynolds number $Re_c$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e)</td>
<td>0.3</td>
<td>6</td>
<td>40,000</td>
</tr>
<tr>
<td>(f)</td>
<td>0.3</td>
<td>6</td>
<td>60,000</td>
</tr>
<tr>
<td>(i)</td>
<td>0.3</td>
<td>6</td>
<td>120,000</td>
</tr>
</tbody>
</table>

Since the goal of the manuscript is to compare the flow field around the three-dimensional wing models with the flow field around a natural wing, the study focuses on the spanwise position of $2y/b = 0.3$ and an angle of attack of $\alpha = 6^\circ$ since at this position and angle, the dominant flow phenomenon, i.e., the laminar separation bubble, is most prominent for the lower Reynolds numbers. At a Reynolds number of $Re_c = 40,000$ the configuration is referred to as C (e) for the clean, V1 (e) for the model equipped with velvet 1 and V2 (e) for the model coated with velvet 2. N (e) represents the measurements performed on the natural owl wing. Analogously, the flow field at $Re_c = 60,000$ and $Re_c = 120,000$ are referred to by the letter ‘f’ and ‘i’. The results of these three parameter combinations of spanwise position, angle of attack, and Reynolds number were used to compare the model wing and the natural wing flow.

3. Results and Discussion

The analysis of the PIV measurements is divided into three parts. In the first section (3.1), the flow field around the wing models and the natural wing is analyzed in detail. In addition to the study of the flow structures, the measurements of the natural wing are discussed concerning changes in the wing geometry due to the surrounding flow field. Since the wing models possess a high level of stiffness in contrast to the very flexible natural wing, the effects of the flow field on the wing models is negligible. Still, the interaction of the flow field with the wing structure has to be taken into consideration to thoroughly understand the flow field for the natural wing. The corresponding findings are presented in section 3.2 which focuses on the influence of the aerodynamic forces on the overall wing geometry, whereas in section 3.3 the movement of the natural wing's trailing edge is investigated. The overall discussion of the flow field with respect to the impact of the deformation is given in section 3.4.

3.1 Flow field analysis

The PIV measurements yield the fundamental data to determine, two-dimensional averaged velocity fields normalized by the freestream velocity, time-averaged Reynolds shear stress distribution and spatial two-point correlations such that the temporal and spatial development of the large scale vortical structures can be analyzed.

Figure 9 shows the normalized averaged velocity fields for the three models and the natural wing at $2y/b = 0.30$, $Re_c = 40,000$, and $\alpha = 6^\circ$. The clean wing model (fig. 9a) possesses a distinct separation bubble with a bubble length of $l_b = 0.3$. Also the model equipped with velvet 2 in fig. 9c shows a region of flow separation with a length of $l_b = 0.35$. Moreover, the model coated with velvet 1 does not indicate a separation bubble in the average velocity distribution (fig. 9c), but patterns of flow separation can be found in the not illustrated instantaneous flow field. Thus, the velvet structures possess the ability to interact with the near-wall flow and as such can influence the separation on the suction side of the wing. The flow around all wing models shows a strong thickening of the boundary layer. For the clean and velvet 2 model the thickening is directly connected to the separation bubble.

The averaged velocity field on the upper side of the natural wing is given in fig. 9d. Note that the differences in the gray shaded areas representing the wing profile are caused by the different viewing angles due to the unequal setups and minor differences in the wing geometry itself. Unlike the artificial models, the flow on the upper side of natural wing is fully attached and does not show any sign of flow separation in the averaged and instantaneous flow fields. A thickening of the boundary layer can be only found at high streamwise positions and is significantly smaller compared to the artificial models.
Note that due to the reflection of the natural wing caused by its geometry and surface structure, the flow field in the direct vicinity of the wall is difficult to be resolved. Nevertheless pronounced flow separation as found for configurations C (e) and V2 (e) could not be detected. Also, no significant thickening of the boundary layer as usually observed in the presence of a separation bubble or laminar-to-turbulent transition could be found for more upstream positions.

The time-averaged Reynolds shear stresses $R_{uw}$ can be used to analyze the momentum transfer into the boundary layer and thereby detect the point of transition onset. The Reynolds shear stresses are defined as $R_{uw} = -\overline{u'w'/u_{\infty}^2}$, where $u'$ and $w'$ represent the velocity fluctuations parallel and perpendicular to the surface and $u_{\infty}$ is the freestream velocity. According to Burgmann et al. [6], the location of transition onset is defined as the point where the average rate of change of the maximum Reynolds shear stresses with respect to the streamwise $x$-coordinate is at least doubled compared to the slope further upstream.

Figure 10 shows the chordwise time-averaged shear stress distribution. The clean and the velvet models all show a strong increase in Reynolds shear stress, although the overall shear stress level is reduced for the velvet 1 model. The strong rise of $R_{uw}$ for configurations C (e) and V2 (e) is directly connected to the
presence of the separation bubble. For the natural wing an increase of the Reynolds shear stresses can be only detected at higher chordwise positions, indicating a significantly longer state of laminar flow.

![Figure 10](image)

**Fig. 10** Maximum Reynolds shear stress distribution for the clean, velvet 1, velvet 2, and natural 'e'-configuration:

\[2\gamma/b = 0.30, \text{Re}_c = 40,000, \text{and } \alpha = 6^\circ.\]

Also, the shear stress level is considerably lower, although the level converges to the trailing edge, indicating a transitional or turbulent flow also for the natural wing. This is in good agreement with the findings of the averaged velocity field in fig. 9.

Note that the velvet 1 model and the natural wing show comparable shear stress values at higher chordwise positions. The major difference is the laminar-to-turbulent transition which is forced for velvet 1 at \(2\gamma/c = 0.35\). Thus, although in neither case flow separation can be found, the mechanisms leading to the attached flow fields are completely different. Furthermore, since the geometry is similar and the velvet structures are found to affect the flow around the wing models, the application of the velvet surface is not the only parameter influencing the flow field around the natural wing, leading to the attached, mainly laminar flow field.

The normalized averaged velocity fields of configuration ‘i’ are given in fig. 11. For this configuration, only the Reynolds number, i.e., the freestream velocity, is changed to \(\text{Re}_c = 120,000\) compared to configuration ‘e’. It is clearly visible that the increase of the Reynolds number significantly affects the flow field around the three wing models. No separation bubble is found in contrast to the findings at the lower Reynolds number. For configuration C (i) the flow stays fully attached even in the instantaneous flow fields. The boundary layer shows only a weak thickening at higher chordwise positions. Configuration V2 (i) depicted in fig. 11c shows a mediocre thickening of the boundary layer and only a few negative \(u\)-velocity components in the instantaneous flow fields. The same tendency can be detected for configuration V1 (i) with a larger thickening of the boundary layer compared to C (i) and V2 (i). Similar to the lower Reynolds number, a significant thickening of the boundary layer can be only found at higher chordwise positions for configuration N (i).
3.2 Contour detection

In contrast to the rigid wind tunnel models, the flexible natural wing is deformed by the aerodynamic forces. To evaluate the influence of the flow, i.e., freestream velocity and angle of attack, on the wing geometry, the laser light reflection line was analyzed using the PIV images. The definition of the contour line was based on the detection of the upper and lower border of the reflection line. Due to the application of the bandpass interference filters, the thickness of the reflection line was less than \(5\ \text{px}\). The centerline of the reflection was determined by a polynomial fit based on the mean distance between the upper and lower border. The resulting approximation is called ‘contour’ line.

The mean contour line was determined by the evaluation of 1000 images. The resulting 1000 single contour lines were averaged to obtain the mean contour line for each configuration. As described in section 2.2 bandpass interference filters were applied to the cameras to reduce the reflections of the wing surface and ensure an adequate mapping of the contour line. Note that in this study only the reflection line of the upper side of the wing is analyzed. No conclusions can be drawn on the camber of the wing since the definition of the camber line requires data of the shape of the upper and lower wing surface.

However, the region close to the trailing edge is only made of layers of single feathers, the secondary remiges in the proximal and the primary remiges in the distal part of the wing (fig. 1). Thus, the thickness of the wing at this location is very small and the feathers are slightly cambered. The calami of the remiges are connected to the ulna of the handbone, i.e., are mounted at a single location at the leading edge. The aerodynamic forces resulting from the normal and shear stress distribution are able to deform the caudal part of the wing depending on the flow field, i.e., Reynolds number and angle of attack. Although no information is available on the lower side of the wing and therefore no conclusions can be drawn on the wing’s camber, it is assumed that due to the mounting situation and the structure of the caudal part of the wing the curvature \(\kappa\) can be used as a measure for the deviation of the flow at the trailing edge and hence, the acting aerodynamic forces.

The maximum curvature of the contour line in percent can be calculated by

\[
\kappa = \frac{\max_{i} \left( \frac{z_i}{c} \right) - \min_{i} \left( \frac{z_i}{c} \right)}{c} \times 100
\]
\[ \kappa_{\text{max}} = \frac{\Delta x_{\text{max}}}{x_{\text{FD}} - x_{\text{FD}}^b} \cdot 100, \]  

(2)

where \( \Delta x_{\text{max}} \) is the maximum distance of the contour line to the abscissa, and \( x_{\text{FD}} \) stands for the \( x \)-coordinate of the ‘first detection point’. Note that due to the weak reflection in the nose region, it is not possible to extract the reflection line in the vicinity of the leading edge. Hence, the term ‘first detection point’ refers to the first point of the reflection line which can be adequately detected. \( x_{\text{FD}} \) represents the \( x \)-coordinate of the trailing edge. In contrast to the leading edge, the position of the trailing edge can be identified precisely due to the distinct reflection line in this region. To quantify the influence of the freestream conditions, the integrated curvature \( \kappa_{\text{int}} \) is introduced as:

\[ \kappa_{\text{int}} = \int_{x_{\text{FD}}/c}^{x_{\text{FD}}/c} \kappa(x) \frac{d x}{c}. \]  

(3)

Figure 12 presents the contour lines for the natural wing at \( 2y/b = 0.30, \alpha = 6^\circ \), and the Reynolds numbers of \( Re_c = 40,000, Re_c = 60,000, \) and \( Re_c = 120,000 \). Note that the scaling of the axis was adapted to illustrate the differences in the wing’s curvature. The contour lines at the first detection point located at approximately \( x/c = 0.35 \) are very alike. Upstream of this region no contour line could be detected. The high similarity between the contour lines is caused by the structure of the wing. In the nose region, the wing possesses a high thickness due to the combination of bones and tissue, i.e., the stiffness of the structure is considerably higher than in the trailing edge region which is only built up of feathers. Therefore, the aerodynamic forces applied to the wing due to the surrounding flow field are not sufficient to deform or deflect the nose region of the wing. Only the aft part of the wing shows a pronounced aeroelastic response.

In contrast, the distributions of the contour line for chordwise positions \( x/c \geq 0.40 \) differ depending on the Reynolds numbers, although the shape for configuration N (e) and N (f) is very similar. At the lower Reynolds number, the acting aerodynamic forces are significantly smaller than at higher Reynolds numbers since the pressure distribution scales by \( u_{\infty}^2 \). That is on the one hand, the lift is approximately one order of magnitude larger than the drag. On the other hand, the structure of the wing has a large stiffness in the \( x \)-direction, whereas the wing possesses a high level of flexibility in the \( z \)-direction. Hence, the deformation of the wing in the streamwise direction is neglected for the current investigation. Unlike the two lower Reynolds numbers, the distribution of configuration N (i) differs significantly due to the higher freestream velocity. The curvature is much smaller than that at the lower Reynolds numbers. This is also quantified by tab. 5 which presents the values of the maximum and integrated curvature as well as the chordwise location of the point of maximum curvature. It shows that \( \kappa_{\text{int}} \) is decreased by approximately 16% for N (e) compared to N (i) whereas the location of maximum curvature is very similar for all Reynolds numbers.

From fig. 12 and tab. 5 it is clear that the Reynolds number has a strong influence on the curvature and hence, the deflection of the flow at the trailing edge. At the lower Reynolds number, the integrated and maximum curvature is higher. That is, at the increased flight velocity, i.e., Reynolds number, the curvature of the wing can be drastically reduced to achieve a similar lift since the lift is proportional to \( u_{\infty}^2 \).
The primary function of the lift is to compensate the weight of the owl, enabling the owl to fly. Since the weight and thereby the required lift of the owl is constant during a flight period it is assumed that the decrease of the wings’ curvature by aeroelastic effects at higher Reynolds numbers acts as an active lift-control mechanism, providing a similar lift force independent of the flight velocity.

3.3 Trailing-edge tracking

Unlike the rigid wind tunnel model, the natural wing is not only deformed by the overall normal and shear stress distribution as described in sec. 3.2 but also deflected dynamically due to phenomena in the local flow field. Due to the structure, the location of maximum dynamic deflection is the trailing edge of the wing. Therefore, the analysis of the wing’s movement is based on tracking of the contour line at the trailing edge. 1000 images were used to ensure a statistically sound analysis of the movement. The terms ‘upward’ $\delta_{up}$ and ‘downward’ deflection $\delta_{down}$ refer to a mean location of the trailing edge which was calculated based on the average coordinate of the trailing edge in the 1000 images. The corresponding values are given in tab. 6.

For a given angle of attack, the amplitude of the trailing-edge movement strongly depends on the Reynolds number. Only a very small deflection of the trailing edge is found for configuration N (e), hence this case is considered static, i.e., the contour line is alike for all images. The configurations at the higher Reynolds numbers show an increasing amplitude for rising Reynolds number. The overall maximum deflection is in the range of 5% chord at $Re_c = 120,000$, which indicates a significant influence on the entire flow field around the wing. This impact is not incorporated in the rigid wing models, resulting in a different character of the flow field especially at higher Reynolds numbers which is already illustrated by the flow fields discussed in sec. 3.1.

3.4 Combined flow field and contour analysis

From the analysis of the contour line and especially the trailing edge deflection it is assumed that the deformation of the natural wing is not attributed to the flow field on the upper side since no dominant flow feature which would be able to cause such a deformation is found (sec. 3.1). Thus, the lower side of the wing is investigated to identify the phenomenon responsible for the wing’s deformation.

Figure 13a presents the flow field on the lower side for configuration N (i). This configuration was selected since it shows a thin boundary layer out almost the entire upper side (fig. 11d) and the largest amplitude of the trailing edge motion (tab 6). In contrast to the upper side, a very thick boundary layer is clearly visible for the entire chord length on the lower side. Even a region of flow separation is found at lower chordwise positions, i.e., $0.46 \leq x/c \leq 0.8$. Hence, the flow field on the lower side differs significantly from the thin boundary layer on the upper side. Therefore, it is considered that the wing’s deformation is mainly caused by the flow field on the lower side of the wing.
To evaluate the influence of the flow field on the lower side on the wing’s deflection spatial two-point correlations of the wall-normal velocity fluctuations $w'$ were used to analyze the vortical flow structure around the wing.

The distribution of the local maxima and minima of this two-point correlation indicates the average streamwise extent of a shed vortex and the distance between two consecutive vortices. Also, the areas of strong correlation describe where the vortices arise and how their size develops downstream of the correlation point. The two-point correlation of the wall-normal velocity fluctuations are calculated by

$$r_{ww} = \frac{w'(x)w'(x + \Delta x)}{w'(x)^2},$$

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

Figure 13b shows contours of $r_{ww}$ on the lower side for configuration N (i). Large vortical structures are clearly visible even at smaller chordwise positions. These large vortices propagate downstream and interact with the wing structure, especially at the trailing edge, inducing the deflecting motion which was analyzed in sec. 3.3. Therefore, the movement of the wing is not dominated by the flow field on the upper but the lower side.

Note that no PIV measurements were performed on the lower side of the rigid wing models, which is why no direct comparison of the induced flow features is possible. Still, the flow field in the wake region of the models does not indicate large vortical structures originating from the lower side. Hence, it is fair to state...
that not only the flow on the upper side but also on the lower side differ considerably between the artificial models and the natural wing.

4. Conclusion
High-speed PIV measurements were performed on a wing model which possesses a geometry that is based on the wing of a barn owl. Since the owl’s wing possesses a unique surface structure which significantly influences the flow field around the wing, two wind tunnel models were further equipped with artificial textiles to mimic the natural structure of the natural owl wing in addition to the alike wing geometry. The measurements which incorporate the owl-based geometry and surface were compared to experiments performed on a prepared natural wing to evaluate the similarity and differences of the corresponding flow fields and hence rank the significance of the aforementioned parameters.

It was found that the owl-based wing model possessed a separation bubble on the suction side of the wing at lower Reynolds numbers whereas it diminished at higher Reynolds numbers. Additionally, the artificial surfaces showed a strong influence on the flow field since the extent of the separation bubble normal and parallel to the wing surface was altered for both velvets, although the impact of the textiles strongly depended on the Reynolds number. In contrast, no separation on the suction side of the natural wing was found for the entire Reynolds number regime.

Furthermore, the distribution of the Reynolds shear stresses was evaluated to investigate the location of transition onset. For the lowest Reynolds number of $Re_c = 40,000$ all models showed a distinct point of laminar-to-turbulent transition at lower chordwise positions whereas the flow around the natural wing possessed a laminar state for the main part of the chord with a slight Reynolds shear stress increase in the vicinity of the trailing edge. Hence, the basic flow state differs significantly for the upper side of the artificial models compared to the natural wing.

To evaluate the impact of the flexibility of the natural wing in contrast to the rigid models, the corresponding laser light reflection line of the upper side of the natural wing was analyzed. It was found that the curvature of the wing strongly depends on the Reynolds number in the sense, that it was significantly reduced at the highest Reynolds number. The flight velocity of the owl indicates an active lift-control mechanism which leads to a reduction of the wing’s curvature to provide a constant lift within the flight velocity range of the owl.

In addition to the investigation of the wing curvature, the deflection of the trailing edge was measured. It showed that the trailing-edge movement also depended on the Reynolds number since at low Reynolds numbers the behavior of the wing can be considered static whereas at $Re_c = 120,000$ a maximum amplitude of approximately 5% chord was found, indicating a considerable impact on the surrounding flow field.

Since no dominant flow feature which could be responsible for the strong deformation of the natural wing was found on the upper side, the lower side of the natural wing was investigated. It showed that it possessed a thick boundary layer for the entire chord length. Also, large vortical structures propagating downstream were found. These vortices interact with the trailing edge, inducing the wing’s deformation. In contrast, although no PIV measurements were performed on the lower side of the models, no evidence for comparable large structures was found in the wake flow of the artificial models. Therefore, it can be concluded that the flow fields on the upper and on the lower side differ significantly for the artificial wing models and the natural wing.

Several reasons for the diverging flow fields of the wing models and the natural wing can be identified. First, minor differences in the basic wing geometry cannot be avoided although the same class of profiles can be assumed. Second, due to the flexibility of the wing, the geometry of the natural wing varies depending on the flow condition, a behavior which cannot be mimicked by any rigid model. Also, the transmissibility of the natural wing might influence the flow field on the upper side. Furthermore, the lower side of the natural wing does not possess the smooth or slightly rough surface of the artificial wing models. The coverts induce a significantly larger surface roughness and are able to interact with the flow, resulting in the very thick turbulent boundary layer and the large vortical structures which interact with the trailing edge and trigger the deformation of the natural wing.

It can be concluded that, although the geometry of a natural barn owl wing and the corresponding surface structure can be transferred into a wing model, the model only partially suitable to mimic the complex system of the natural wing. Still, the results found for the artificial wing models might be able to enhance the
flight performance of MAVs since the separation bubble as dominant flow feature could be influenced by the artificial surfaces.

5. References