DESIGN AND AERODYNAMIC ANALYSIS OF AN AIRFOIL WITH A BIOINSPIRED LEADING EDGE DEVICE FOR STALL MITIGATION AT LOW REYNOLDS NUMBER OPERATION

BY

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THESIS

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Abstract

Robust and predictable aerodynamic performance of unmanned aerial vehicles at the limits of their design envelope is critical for safety and mission adaptability. Deployable aerodynamic surfaces, such as flaps or slats, from the wing leading or trailing edges are often used to extend the aerodynamic envelope. One such aerodynamic device is the Alula, a feather structure attached to one of the hand digits of a bird’s wing. The alula is extended by birds at high incidence angles and has been shown to improve the stall parameters of the wings. In this study, a series of wind tunnel experiments are performed to quantify the effect of various deployment parameters of an alula-like leading edge device on the aerodynamic performance of a cambered airfoil (S1223). The alula relative angle of attack, measured from the mean chord of the airfoil, is varied to modulate tip-vortex strength, while the alula deflection is varied to modulate the distance of the tip vortex to the wing surface. Boundary layer velocity profile measurements taken at $x/c = 1.25$ along the chord length and at three locations along the span of the airfoil show fuller BL profiles in the area of influence behind the alula. The resulting re-energizing of the BL at post stall angle of attacks delays flow reversal and separation and decreases associated drag. Results show that as alula deflection ratio, $\gamma$, increases, the lift coefficient, also increase. At post stall angles of attack, the wake velocity deficit zone is shown to reduce in size when the alula is deployed, confirming that the wing adverse pressure gradient is reduced. The results are in strong agreement with the measurements taken on bird wings with alulae. With the ability to change alula parameters such as location, size, deflection and angle, the complete wing configuration can be tuned for mission specific aerodynamic requirements.
Dedication

The field of experimental aerodynamics requires solid dedication, patience, attention to
details, time and most importantly help from faculty, fellow students and family. I would
like to thank my wife, Lydia for enduring the demanding nature of graduate school with
me. Lydia was instrumental in not only keeping me going through research stagnation
but also helping me break through scientific roadblocks. Her detail oriented, inquisitive
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taking turns making coffee.
Acknowledgments

I would like to express my gratitude to my advisors Assistant Professor Aimi Wissa and Assistant Professor Leonardo P. Chamorro for their dedicated guidance, unreserved assistance and personal example. This work was shaped primarily by their insight, experience and passion for the subject.

I am thankful to my lab, Bio-inspired Adaptive Morphology Lab and its members for their help with experimental and theoretical assistance. Special thanks to Michael Lynch who has been an inseparable part of my research. Michael is the key person behind many of the critical research tools I had built and was always there when assistance was needed.

Resources from the Renewable Energy and Turbulent Environment group were instrumental in conducting all of the experimental work presented in this work. Yaqing Jin provided assistance with wind tunnel experimentation techniques, instrumentation and data processing and Ali Hamed helped with PIV setup, calibration and data post-processing.

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Nomenclature

\( \alpha \) Wing angle of attack (AoA)

\( \mathcal{A} \) Wing aspect ratio

\( \beta \) Alula chord relative angle to wing chord line

\( \epsilon_{sb} \) Solid blockage

\( \gamma \) Alula deflection angle

\( \nu \) Kinematic Viscosity, Air

\( \rho \) Density of air

\( b \) Wing span

\( b_A \) Alula span

\( BL \) Boundary layer

\( C \) Wind tunnel cross section

\( c \) Wing chord length

\( c_A \) Alula chord length

\( C_d \) Drag Coefficient

\( C_l \) Lift Coefficient

\( C_p \) Pressure coefficient

\( D \) Wind tunnel depth

\( H \) Wind tunnel height

\( h_A \) Alula deflection

\( K_1 \) Test article volume

\( L \) Lift generated by wing
$LE$  Airfoil leading edge

$p_0$  Total pressure

$p_1$  Static pressure

$q_\infty$  Flow dynamic pressure

$Re$  Reynolds number

$S$  Wing surface area

$TE$  Airfoil trailing edge

$U$  Averaged velocity component in the freestream direction

$u'$  Velocity fluctuations in the freestream direction

$V$  Averaged velocity component normal to freestream direction

$v'$  Velocity fluctuations normal to freestream direction

$V_\infty$  Freestream velocity

$x/c$  Airfoil chord location, normalized by chord length

$z(c)/c$  Airfoil thickness distribution, normalized by chord length
1 Introduction

Life has been evolving for millions of years, adapting to the environment and specializing in ecological niches. Examples of such morphological adaptation are ubiquitous. Swimming and flying require special physiological apparatus, such as leading edge (LE) devices on marine mammals’ flippers and on birds’ wings, that allow for efficient and versatile operation. Morphology differs between species but generally employs vortex generation techniques to achieve various performance enhancements. Tubercles on the flippers of the humpback whales, for instance, act as passive-flow control structures which modify the flow over the flipper to delay stall and increase the effective span [8,16,20]. There are many examples of unique physiological characteristics which birds have developed including elliptical wings, short or long hands wings, covert feathers, etc. [23]. The alula is one of such distinguishable devices utilized by birds to improve their flight capabilities. It is a small wing-like structure (Figure 1) located between the hand wing and the arm wing. The Alula is usually covered by 2-6 remiges and is attached to the first digit bone (Figure 1(c)) [26]. Unlike fixed wing aerial vehicles, birds use and adapt their entire bodies for the successful performance of the maneuver or task at hand. Taking off and landing, maneuvering or catching prey, each require unique aerodynamic capabilities. When landing, for instance, the bird enters a controlled descent, continuously reducing its speed. However, since the lift generated by the bird’s wings has to equal its weight, the wings’ angle of attack (AoA) has to be increased. Immediately before the end of the maneuver, the AoA exceeds the stall angle, and the wing may lose its ability to generate lift [4]. For such a maneuver to be executed in a controlled manner, a stall prevention device such as the alula is essential.

1.1 The Alula: Morphology and Aerodynamic Effects on Avian Flight

The alula affects the airflow in two distinct aerodynamic ways. By extending over the upper surface of the airfoil, the alula is modifying the pressure distribution around the wing leading edge, increasing the capacity of the airfoil to sustain higher pressure gradients. This
effect is similar to a leading edge slotted flap of a fixed wing aircraft. Traditional leading edge devices, such as slots and flaps, reduce the magnitude of the LE pressure gradient, delaying flow separation at high angles of attack [1, 19]. Slots have been shown to increase the maximum lift coefficient of a wing by 37% and delay the stall angle by $24^\circ$ [1, 28, 29]. As described by Abbot and Doenhoff [1], a good boundary layer control device can delay separation of both leading edge laminar flow as well as aft turbulent flow. The second effect of the alula is in the generation of a streamwise tip-vortex. The tip vortices generated by at the alula tips impinge the boundary layer, injecting momentum and delaying flow reversal at steep angles of attack. These two effects can be classified as a 2D slot effect and as 3D tip vortex generation. A good understanding of these coexisting aerodynamic effects will enable better design of such leading edge devices, which can lead to lower take-off and landing speeds as well as higher maneuverability.
1.1.1 Morphology of the Alula and Relation to Avian Wing Morphology

Alvarez et al. [3], Crowford and Greenwalt [11], Savile [24] and Norber [18] have studied the flight of a number bird species. Norberg [18] discusses bird morphological flight parameters such as mass, length and area [18]. Norberg et al. analyze important morphological parameters, such as aspect ratio (\(A\)) wing loading (\(W\)), bird weight and flight speed, to distinguish between several types of bird flight. Based on their form and function, wings are classified in four different types, Class A through D, as shown in Figure 2 [3, 12, 18, 24, 27]. Important functional relationships between alula size, position, wing \(A\) and \(W\) are reported in references [24] and [3]. Class A birds, such as the Kingfisher, Common Blackbird, Goldfinches, are efficient at low to moderate speeds. Their elliptical wings generate elliptical lift distribution and smooth tip vortices, suitable for living in forests and confined spaces [3]. With low to medium \(W\) and good flight control, they are adapted to frequent take offs, landings and accurate maneuverability.

Class B are high speed wings of migratory birds or birds of open spaces such as the Swallow, Dove and Kestrel. Their wings are characterized by low camber, moderate to high \(A\) and

\[\text{Figure 2: Bird wing types based on their morphology and adaptation. Adapted from [21].}\]
pronounced sweepback. *The Seagull and the Albatross* belong to class C with high AR, high speed wings. They are mainly adapted to flight over water surfaces and well suited for dynamic soaring [3]. Class D birds (*Owls, Storks*) generally have high lift, moderate aspect ratio wings. Their wing tips are slotted and usually have an alula, making them very efficient at low speeds and static soaring over land [3].

Meseguer *et al.* [15] concluded that the alula plays an important role in the flight of birds with a higher frequency of take offs and landings and who require good maneuverability. This is supported by the fact that the relative length of the alula to the length of the wing decreases as the wing $AR$ increases. The length of the alula is also correlated with the wing loading - low wing loading corresponds to shorter alulae. For example, slow flying birds (class D birds) require higher lift and better stall control as compared to the moderate and high speed fliers in class B and C.

In summary, the alula is a structure which has evolved to expand the flight envelope capabilities of birds. With no detrimental effect on high speed and gliding flight, it reduces the risk of flow separation at extreme low speeds and AoA. Moreover, the aerodynamics of bird wings with alulae are explored in detail [5, 13, 17], however, research is lacking in describing the effects of varying morphological parameters of the alula on aerodynamic performance. The goal of this study is to provide insight into the flow around a low Reynolds number, high-lift airfoil near stall regimes equipped with an alula-type device. Varying geometrical parameters (relative AoA and deflection) of this device allows for a better understanding of the aerodynamics and the relative effect on the performance of the airfoils. Expanding the knowledge of such a device will assist in the design of low *Re* unmanned aerial vehicles (UAVs) with higher mission adaptability and an extended flight mission envelope.

### 1.2 The Aerodynamic Effect of the Alula on Avian Flight

A few studies have been conducted to unravel the function of the alula and its aerodynamic effects [3, 5, 13, 17]. These studies used a combination of PIV (Particle Image Velocimetry), lift-drag measurements, hot-wire anemometry and other methods to quantify birds’ wing
performance and limitations. The majority of reported investigations are conducted on either live birds or dead bird wings. Aerodynamic testing often requires long and exhaustive experimental matrices, often resulting in deterioration of the test specimen, which means that the results should be interpreted with caution.

The alula is present in a vast number of bird species, attesting to its usefulness and the performance gains it delivers. This fact is supported by many experimental and numerical investigations. Wind tunnel test results by Lee et al. showed that when the alula is deployed, the wing of the adult male magpies generates 1-12% more lift and delays stall by 5-10° [13]. Furthermore, Austin and Anderson [5] showed that the Lesser Scaup had a 10% increase in lift when the alula deflected. They tested the wings at various flow speeds ranging from 7 to 20 m s\(^{-1}\) and AoA from -10° to 35°. They found that in all the three tested birds, the Wood Duck, the Black Scoter and the Lesser Scaup, the alula deflected at a specific velocity and AoA. Figure 3 shows that the alula deflection envelope increases in relation to AoA and the flow velocity. An interesting observation is that the alula deflects at a specific combination of velocity and AoA, but after a certain maximum AoA and velocity, it closes again. In Figure 3, Austin and Anderson indicated the maximum alula deflection conditions with a data point. Between the initial alula deployment and closure, there is a constant deflection angle increase as the flow velocity increases. PIV results indicate that the flow behind the wing with the alula deployed is faster and always non-reversed [5]. Even though the average flow velocity field is non-recirculatory in tests with the alula not deployed, inspection of the instantaneous velocity field images show areas with flow reversal [5]. This may suggest that the effect of the alula may also lay in its ability to reduce stall risk in addition to being a lift enhancing device.

Lee et al. [13] conducted a series of experiments to better understand the aerodynamics of a wing with an alula. They concluded that, when deployed, the alula remiges create a set of counter-rotating vortices moving downstream (Figure 4). The shear layer thickness over the top surface of the wing is decreased by the faster streamwise flow from the downwash flow vector created by the alula tip vortices [13]. The thinner shear layer causes delayed flow separation over the top of the bird wings from the vicinity of the alula towards the wing
A trend can be observed in which the AoA at which maximum deflection occurs increases with higher velocities. Also, the minimum AoA for alula deflection decreases for an increase in velocity. Adapted from Austin and Anderson [5].

tips. Furthermore, as the main wing AoA increases, the alula tip distance from the wing LE increases. This mechanism prevents the wing from losing its circulation due to viscous dissipation near the LE surface [13]. The authors also measured the relative angle between the alula and the wing chord lines to be -29°, suggesting that the alula does not help to generate additional lift at low AoA of the main wing [13]. Only at extreme wing AoA, the alula relative AoA to the freestream is high enough to generate strong tip vortex, imparting sufficient momentum on the suction side of the wing. This agrees with test results of leading edge slot devices on fixed airfoils where the slot chord angle of -25° to -35° provides the bulk of the performance increase, and further angle increases results in marginal improvements [29]. Furthermore, the rotation of the streamwise tip vortex induces spanwise velocity over the wing in the distal direction. In Figure 5, the boundary layer velocity profile with the alula deployed shows a delayed flow reversal compared to the clean wing. This mechanism suppresses the flow separation further and is more pronounced in the regions outside of the alula wing tip [13].

Figure 3: Alula deployment envelope. Data points indicate AoA for maximum alula deflection. A trend can be observed in which the AoA at which maximum deflection occurs increases with higher velocities. Also, the minimum AoA for alula deflection decreases for an increase in velocity. Adapted from Austin and Anderson [5].
Figure 4: Cross sectional planes of mean $U$ and $V$ velocity fields obtained from PIV tests show flow reversal delay when the alula is deflected (a). Span-wise cross sections of the mean velocity vectors through the alula wing show increased velocity of the alula compared to the baseline (b). Counter-rotating tip vortex formation from alula tips are shown in (c). Adapted from Lee et al. [13]

1.3 Current Research Goal, Hypothesis and Objectives

Previous work explored the function of the alula and its correlation to other morphological parameters in the context of habitat, lifestyle and bird flight requirements. While the aerodynamics of bird wings with alulæ have been explored in detail, no research exists in describing the effects of varying morphological parameters of the alula on aerodynamic performance. Mission adaptability and maneuverability are key requirements for the design of engineered aerial vehicles. This parametric study provides a better understanding of the
alula aerodynamics and will enhance the aerodynamic design tools available.

The goal of this study is to test the hypothesis that a bioinspired leading edge alula device (LEAD) can improve the flow characteristics of an airfoil in low-to-moderate Reynolds numbers through force balance measurements, hot-wire anemometry and PIV analysis. Bird wings are complicated flight devices with multiple control surfaces, morphing abilities and dense sensory network that have evolved the ability to adapt to many flight modes instantaneously. In contrast, man-made aerial systems are often rigid structures with limited adaptability. The LEAD tested is a rigid aerodynamic surface allowing for a controlled analysis of each variable morphological parameter, i.e. alula AoA and deflection. Thus through an experimental matrix, the aerodynamic effect of the alula AoA and deflection angle is quantified.

Furthermore, an attempt is made to provide an experimental validation to findings from previous investigations of bird wings equipped with an alula. The hypotheses tested are:

- The LEAD effective operational envelope, where performance improvements are possible depends on $Re$ and wing angle of attack. This hypothesis will be proven if it
is found that the LEAD has negative effect on airfoil performance at pre-stall and positive effect in the post-stall AoA at the tested Reynolds numbers.

• The LEAD affects the upper surface of the wing by inducing higher near-wall velocities through re-energizing the BL with its tip vortex. Proving this hypothesis requires that the affected zone behind the LEAD expands in a similar fashion as a trailing tip vortex and that this zone shows higher near-wall flow velocities and delay in flow reversal chord location.

• The LEAD relative AoA is such that to provide favorable local airflow conditions for the alula to operate efficiently. Thus at higher wing angles the LEAD is expected to show better improvements with lower relative AoA. Thus, if decreasing the relative alula angle with higher wing AoA show better performance, this hypothesis will be validated.

In this work, a low speed wind tunnel is used to test the effect an LEAD on the airfoil performance ($C_l, C_d$), boundary layer and wake structure. Two variable design parameters of the device are tested in a combination of varying flow velocity and airfoil angle of attack. As discussed previously, an alula feather structure is shown to affect the wake and boundary layer of birds’ wings [5,13]. Meseguer et al. conducted a series of experiments varying alula model parameters with clear improvements in $\Delta C_L$ [15]. However, the alula test specimen was crafted from an aluminum sheet with unknown camber and no alula relative angle is provided. In this study, the alula cross section is selected to be NACA 22 in order to provide better repeatability. Expanding the investigated alula variable parameters an experimental test matrix is designed to provide information on the effect of $Re$, wing angle of attack, $\alpha$, alula relative angle of attack, $\beta$, and alula deflection angle, $\gamma$. 
2 Methodology

The effect of the LEAD on the airfoil aerodynamics is evaluated in three distinct ways: (1) a force-torque sensor is used to evaluate the aerodynamic performance behavior, i.e. change in lift and drag coefficients; (2) a hot-wire (CTA) probe is used to analyze the airfoil wake by sampling a discrete number of points in the normal to the flow direction, thus providing high frequency flow statistics; (3) particle image velocimetry (PIV) is used to extract the full vector field of select wing and ahula configurations. The combination of the aforementioned approaches provides an insight into the flow mechanisms of an airfoil in the presence of a leading edge device, such as the ahula.

2.1 Wings in Nature

Liu et al. [14] performed non-contact surface measurements on bird wings using a 3-dimensional laser scanner. Using videos of level flight for Seagull, Merganser, Teal and Owl Liu et al. constructed the upper and lower wing surfaces from the mean camber line and the thickness distribution. Reconstruction of the wings provide spanwise distribution of chord length, camber and thickness, from which 2D cross sections are extracted, shown in Figure 6. Based on the wing characteristics the authors compared the scanned wings and their cross sections to the high-lift low-$Re$ airfoil S1223 also shown in 6. Comparison of $C_p$ distributions between S1223, Seagull and Merganser airfoils show similarity in the laminar separation bubble and the subsequent pressure recovery region. In a different study, Carruthers et al. conducted a multi-station photogrammetry using six high-resolution digital cameras to reconstruct the 3-dimensional upper and lower surface topography of the Steppe Eagle *Aquila nipalensis* wing during an elevated pitch [6]. The 2D wing sections (airfoils) are extracted using a patterned 2D calibration grid and post processed through MATLAB. The scanned wing geometry of a perch maneuver of the steppe eagle is of high interest for this study for two primary reasons: 1) the wing shape is morphed for high lift and AoA and 2) the steppe eagle is a bird that operates in the $Re$ number ranges of interest. Analysis of the extracted eagle cross sections through XFOIL showed strong sensitivity to Re, resulting in negative impact on $C_l$ and $C_d$. 

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It was also observed that a strong laminar separation bubble is formed at low Re. Performance analysis conducted by Carruther et al. did not investigate the effect of turbulence and surface roughness. Bird wings are covered in feathers and form a specific surface roughness, which may be aiding their ability to perform better at low Re than shown by Carruthers et al. Similarly to the results from Liu et al. [14], Carruthers et al. draw comparison between bird wing sections and two standard airfoils, ClarkY and S1223. They show that $C_l$ and $C_d$ performance of bird airfoils is comparable to that of the standard ones. The airfoil data from the studies by Carruthers et al. and Liu et al. are summarized and compared to that of S1223 in Tables 1 and 2.

2.1.1 Wing Test Specimen

The test parameters used for the experimental matrix are based on previous studies of bird wing shapes, morphological parameters and flight conditions. The choice for the test wing geometry stems from the combined wing planform characteristics shown in Table 1 and the cross sectional airfoil studies shown in Figure 6 [6,14,17]. Furthermore, it is important that validation data exists at low Reynolds numbers for the test specimen airfoil, in order to establish performance metrics, i.e $C_l$. In test specimen model size considerations, the wind tunnel size and load cell range were the primary factors.

<table>
<thead>
<tr>
<th>Bird Specimen</th>
<th>Area $S$, (cm$^2$)</th>
<th>Wing Span $b$, (cm)</th>
<th>Mean Wing Chord $c$, (cm)</th>
<th>$\mathcal{A}$</th>
<th>Alula Length $b_A$, (cm)</th>
<th>Mean Alula Chord $c_A$, (cm)</th>
<th>$\mathcal{A}_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Specimen</td>
<td>171.3</td>
<td>22.5</td>
<td>8.0</td>
<td>2.80</td>
<td>6.7</td>
<td>1.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Black Scoter</td>
<td>206.5</td>
<td>63.5</td>
<td>11.4</td>
<td>5.56</td>
<td>5.1</td>
<td>1.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Lesser Scaup</td>
<td>180.6</td>
<td>53.3</td>
<td>9.5</td>
<td>5.60</td>
<td>3.8</td>
<td>1.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Redhead Duck</td>
<td>240.0</td>
<td>61.0</td>
<td>11.1</td>
<td>5.49</td>
<td>5.1</td>
<td>1.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 1: Wing morphological measurements of various bird species [5].

Airfoil Selection and Parameters

The distal wing airfoil sections for Owl, Teal, Merganser and Seagull are compared to that of the high-lift, low-Reynolds number airfoil section, the S1223, Figure 6(b). The camber line
and maximum thickness of S1223 \( (z_{(c)max}/c = 0.08692) \) are similar to the ones of the merganser \( z_{(c)max}/c = 0.0852 \) and \( z_{(c)max}/c = 0.0579 \) \[14\]. Furthermore, using XFOIL (details on code and origin to follow) the surface pressure coefficient are compared. Figure 6(c) provides an overlay of \( C_P \) curves of the Seagul, Merganser and S1223, all three airfoils exhibit similar pressure recovery region, with the S1223 having a laminar separation bubble (LSB) at \( x/c = 0.25 \) compared to \( x/c = 0.7 \) for the Merganser. The airfoil coordinates were extracted and were analyzed through XFOIL at the same \( Re \) as the test airfoil and are overlayed over the S1223 profile in Figure 7. Similarly to the Seagul and Merganser the mean camber line resembles the one of S1223. Lift and drag coefficient curves show comparable behavior between the two airfoil in their lift-curve slopes as well as in the turbulence transition and stall onset.

Table 2: Camber \( (z_{(c)max}/c) \) of the Merganser and Steppe Eagle are matched by S1223 \[6, 14\]. Maximum thickness \( (z_{(t)max}/c) \) of S1223 is higher,

<table>
<thead>
<tr>
<th></th>
<th>S1223</th>
<th>Merganser</th>
<th>Steppe Eagle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camber %</td>
<td>8.69</td>
<td>8.852</td>
<td>8.2</td>
</tr>
<tr>
<td>Max thickness %</td>
<td>12</td>
<td>5.79</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Thus, the airfoil selected is the S1223, which is commonly used for high lift RC competition airplanes and has been tested at low Reynolds numbers \[25\]. The S1223 has maximum thickness of 12.1\% at 19.8\% chord and maximum camber of 8.1\% at 49\% chord. The \( \mathcal{A} \)R of the wing is being reported regardless of the fact that it is based on a rectangular wing spanning the full wind tunnel height. This is done for the purpose of providing a dimensional similarity between the wing and alula \( \mathcal{A} \).  

Highly cambered wings are often prone to sharp stall behavior, and as such, may be though to be inappropriate for birds, which often operate at extreme AoA. However, aerodynamic devices such as the alula, deployable covert feathers and dynamic aerodynamic and geometric twists allow for precise control of flow reversal and separation. Figure 7 shows the shift in transition to turbulence along the chord line of S1223 and the Eagle’s airfoil. The translation of the transition point with increase in \( C_l \) is gradual up to a point close to \( x/c = 0.5 \) where the slopes depart. This results in more gradual \( x_{tr} \) translation towards the LE in the bird
(a) Laser scanned distal wing airfoil sections for Owl, Teal, Merganser and Seagull.

(b) Comparison between highly cambered, high-lift airfoil S1223 to the Seagull and Merganser proximal wing sections.

(c) Pressure coefficients on top and bottom airfoil surfaces are comparable. $\alpha = 5$

**Figure 6:** Wing airfoil section comparison between various bird species and a high-lift, low-Reynolds number airfoil (S1223), by Selig *et al.* [6,10,14]

Lift curves, drag buckets and transition ramps reported here are generated through a 2D viscous aerodynamic design and analysis code - XFOIL. XFOIL is an open-source inviscid solver with localized viscous boundary layer coupling and is used for obtaining preliminary results with acceptable fidelity at minimal computational cost. The code is based on ISES and details, validation and verification analysis can be found by Drela and Giles [7]. Results from wind tunnel experimental results for S1223, conducted at the Aerodynamics Research Laboratory at University of Illinois Urbana-Champaign, are co-plotted to provide a comparison metric to the XFOIL results [25]. At low Reynolds numbers, i.e. $Re = 100,000$, XFOIL is over-predicting $C_l$ and under-predicting $C_d$. Figure 7. Comparing to the experimental results, the numerical prediction has a an error of $\Delta C_l = 0.5$ and stall angle offset of $4^\circ$. This is a significant error and is attributed to the fact that the S1223 airfoil has been designed with reverse aerodynamic tools based on similar panel methods (ISES, PROFOIL, EPPLER), which result in such favorable estimations. In this sense, the S1223 case can be
Figure 7: S1223 Polar curves show a distinct stall characteristic with $C_l$ starting to diminish at angles between $8 - 12^\circ$ (XFOIL). Transition on upper surface is kept at the T.E. for $C_l = 0 - 1$, i.e. $-6^\circ$ to $-1^\circ$. In the operating range of AoA the transition moves quite rapidly toward the L.E. and at $\alpha = 6^\circ$ transition to turbulence has shifted mostly to the L.E. considered as the lowest fidelity scenario. Regardless of this discrepancy to the experimental results, the purpose of the XFOIL results is to provide a computationally non-intensive analysis of known low Reynolds number airfoils and those of scanned bird wings.

2.1.2 Alula Test Specimen

The alula wing $\mathcal{A}$ and span ($b_A$) are designed to follow biological trends, as shown in Table 1. Since no initial assumptions are made on the alula wing span-loading, the planform is designed with geometrically elliptical chord distribution, as opposed to an elliptical span-
load distribution. Figure 9 shows the spanwise chord length distribution and the planform shape. Alula maximum chord length is 21.8 mm (33% of wing chord) and span is 66 mm (15% of the total wing span). Due to physical interference of the alula root section and the wing upper surface at $\beta = 22^\circ$ the root part of the wing is truncated. The span and chord lengths of the alula-inspired device are 67.5 mm and 18.7 mm respectively.

Figure 8: NACA 22 Polar curves show soft stall characteristics and slow decay in $C_l$ at angles up to $20^\circ$. It should be noted that Reynolds numbers reported are based on wing chord length. Effective $Re$ of the alula based on flow velocity (based on $Re$ of the wing) will be lower.

NACA 22 was selected as the airfoil section for the alula device. The section is often used for leading edge devices in fixed wing applications because of its soft stall behavior and extended AoA. The airfoil geometry has the following parameters: 12% maximum thickness located at 24.2%$c$ and 68% maximum camber located at 54.2%$c$. The NACA 22 airfoil section is selected due to the soft stall and somewhat enhanced post stall region, where increased $C_l$ is sustained until extremely high angles of attack, i.e. $20^\circ$, see Figure 8. Turbulence transition moves towards the leading edge in a linear manner until stall angle ($\alpha = 6 - 8^\circ$)
is approached, approx. at 70% x/c, after which transition quickly reaches the leading edge. The ability of this airfoil to sustain high lift at high angles is favorable since the alula will be deployed at main wing angles of attack beyond stall. The alula local flow may reach stall angle and beyond, hence delay in flow separation is important in improving the overall system lift coefficient.

*Figure 9:* The alula is designed as a wing with geometric spanwise chord distribution. Root section chord length is truncated to avoid interference with the wing surface at high alula angles of attack. The spanwise geometric chord length distribution is driven by 10 spanwise control locations, at which the elliptic function is enforced. The contour is closed with a tangent spline. The alula is attached to the wing via a connector piece that ensures proper $\beta$ and $\gamma$ setting.

In order to ensure repeatable and reliable alula deflection and angle of attack while testing, a connector with specially designed locking mechanism is used. The alula relative to the wing chord angle, $\beta$, is set by the star shaped key features seen in Figure 10. Because of the fact that the locking keys are inseparable from the airfoil, each angle setting, i.e. $-10^\circ, -5^\circ, 0^\circ, 5^\circ, 10^\circ$, is a separately printed alula wing.
Figure 10: Repeatable and reliable alula angle of attack setting is achieved through a set of interlocking channel mechanism that exists on the connector and the alula, as shown. A single alula device can only have a single $\beta$ angle setting.

2.2 Test Parameters

2.2.1 Flight Similarity and Test Conditions

To test the flow conditions of interest in a wind tunnel with limited test section size and a velocity range, flow similarity methods must be used. The Reynolds number is a dimensionless parameter, which expresses the ratio between inertial and viscous forces. The Reynolds number is found by Equation 1, where $U$ is the mean flow velocity, $c$ is the test airfoil chord length and $\nu$ is the fluid kinematic viscosity. Wind tunnel maximum speed is $27 \text{ ms}^{-1}$, which provides a limitation to the size of the airfoil to match the target Reynolds numbers, i.e. low $\text{Re} = 100,000$ and $135,000$. In order to minimize the wind tunnel geometrical solid blockage the airfoil chord to test section length ratio, $c/H$, is kept at 80 mm and the freestream flow velocity is set at $19.4 \text{ ms}^{-1}$ and $26.6 \text{ ms}^{-1}$ for $\text{Re} = 100,000$ and $135,000$ respectively.

$$Re = \frac{Uc}{\nu}$$  \hspace{1cm} (1)

2.2.2 Experimental Test Matrix

The airfoil and alula parameters are selected to analyze post stall and deep stall conditions of the S1223 airfoil in the presence of an alula-like device. Airfoil incidence angles are $\alpha = 10^\circ$
(post stall) and $\alpha = 18^\circ$ (deep stall). The alula is designed with three discrete, adjustable deflection angles, $\gamma = 4^\circ, 13^\circ, 22^\circ$ (see Figure 11 (a)). The angle $\gamma$ is fixed mechanically using the alula device connector, Figure 9(b). There are five alula incidence angles, measured with respect to the main airfoil chord line, $\beta = -10^\circ, -5^\circ, 0^\circ, 5^\circ, 10^\circ$.

![Front View](image1)

![Cross-section of wing and alula.](image2)

![Frontal view of the discrete $\gamma$ alula positions.](image3)

Figure 11: Wing model equipped with alula device showing test parameters, $\gamma$ (a) and $\beta$ (b). Size and mounting of the alula device are apparent from CAD generated graphic.

The alula incidence angle, $\beta$, and tip deflection angle, $\gamma$, can be seen in Figure 11. The wing and alula setup are shown, front view, in Figure 11 (a), and a cross sectional view of the alula relative angle of attack is shown in Figure 11 (b).

In order to characterize the effect of the alula on the airfoil velocity boundary layer profile, a hot-wire probe was placed behind the trailing edge (TE) of the airfoil at $x/c = 1.125$ or 10 mm in the stream-wise direction of the freestream, as shown in Figure 12. At each $Re$, i.e. $Re = 100,000$ and $Re = 135,000$, a baseline test was conducted with the hot-wire positioned at mid-span (equidistant from wind tunnel walls) and translated through the boundary layer (BL), as shown in Figure 12. A baseline test is defined as a test with no alula attached to the airfoil. In the configurations with alula devices, the hot-wire probe is also translated through the BL, however the data is collected at three span-wise locations, namely at -20
mm, 0 mm and 20 mm from the alula wing tip (see Figure 13).

![Hot-wire probe station diagram](image)

(a) Hot-wire probe stations across boundary layer at T.E., $x/c = 1.125$

(b) Sample results - velocity deficit overlayed on airfoil schematic.

**Figure 12:** Hot-wire probe location is fixed for all tests at $x/c = 1.125$ and is translated through the BL of the airfoil.

![Hot-wire probe locations diagram](image)

**Figure 13:** Hot-wire probe locations are offset 20 mm (+/-) from alula device wing tip, with +20 mm inboard, 0 mm at location approximately near the tip and -20 mm outside of wing tip. Note: figure not drawn to scale.

Table 3 provides the full test matrix conducted. The tests presented in this table pertain to the hot-wire boundary layer measurements sequence as shown in Figures 12 and 13.
Table 3: Boundary layer (hot-wire) experimental test matrix. Alula deflection angle is fixed at \( \gamma = 13^\circ \) for all tests.

<table>
<thead>
<tr>
<th>( \alpha^\circ )</th>
<th>( \beta^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re = 100,000</td>
<td>Re = 135,000</td>
</tr>
<tr>
<td>Baseline</td>
<td>Baseline</td>
</tr>
<tr>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>X X X</td>
</tr>
<tr>
<td>18</td>
<td>X X X X</td>
</tr>
<tr>
<td>26</td>
<td>X X</td>
</tr>
</tbody>
</table>

2.3 Wind Tunnel and Experimental Setup

2.3.1 Wind Tunnel

A 2-dimensional airfoil equipped with an alula device was tested in the Talbot Laboratory wind tunnel of the University of Illinois Urbana-Champaign. The wind tunnel is a closed section, open-loop, constant pressure wind tunnel. There are 4 test sections of equal length and a cross section of 44 X 90 cm\(^2\) with optically transparent walls. The first test section was chosen for this analysis due to the less developed, thinner boundary layer and lower turbulence levels (the turbulence intensity of the working section was measured to be 0.1%). More information on the wind tunnel are provided by Adrian et al [2]. The wing section was designed to span the total height of the wind tunnel in order to minimize 3-dimensional aerodynamic effects from wing tip vortex interactions, Figure 16.

2.3.2 Wind Tunnel Boundary Corrections

Blockage effects

The closed section wind tunnel sidewalls restrain the natural curvature of the flow around an airfoil, causing the airfoil to behave as one with extra camber. Also, the presence of
the wind tunnel walls increases the measured flow velocities resulting in an increase in lift, drag and pitching moments. Solid and wake blockage are effects on the flow field as a result from the presence of test section walls. Buoyancy effects have not been considered due to the absence of the wind tunnel longitudinal pressure gradient. Formulation for blockage and wake effects are summarized by Burlow, Rae and Pope [22] and the solid blockage increment is computed using the following relationship:

\[ \epsilon_{sb} = \frac{K_1}{C^{3/2}} \]  

\( K_1 = 0.000174 \text{ m}^3 \) is the model volume and for the test wing specimen and \( C = 0.4275 \text{ m}^2 \) is the wind tunnel test section cross sectional area (Table 1), resulting in solid blockage effect of \( \epsilon_{sb} = 0.1\% \). Wake blockage effects were also considered, but due to the fact that the airfoil is a streamlined object at relatively shallow incidence angles, the effect is negligible. Furthermore, since the trailing vortex system that impinges the boundary layer is weak, the downwash effect corrections will not be considered [22].

Wind tunnel flow velocity is set through a pitot-static tube measurement. Since flow speed is important in setting the correct Reynolds number each test matrix configuration has been calibrated and the correct velocity used to produce the desired Re. Due to the fact that the test section is close to the honeycomb straightener of the wind tunnel inlet the use of splitter plates was not justified. With no splitter plate effect the distance of the static-pitot tube probe location was set at 5 airfoil chord lengths, at which distance the velocity correction increment is found to be minimal (< 3%) [9].

2.3.3 Instrumentation

Pitot-static tube

Freestream velocity was measured using a pitot-static tube, placed ahead of the airfoil test location (see Section 2.3.2 for details). The static and total pressure reading is acquired by the differential pressure transducer, processed and output by a National Instruments DAQ
(NI-DAQ) unit. Differential pressure reading is converted to free stream velocity magnitude using Bernoulli, \( V_\infty = \sqrt{2(p_0 - p_1)/\rho} \).

**Hot-wire Probe and Data Acquisition** A hotwire anemometer was used to get high-resolution measurements of the streamwise velocity at a set of locations as described in further detail in Section 2.2.2. The probe is made of 5.0\( \mu \)m tungsten wire, and connected to a DANTEC Dynamics system. The sampling frequency was set to \( f = 10kHz \) and sampling duration to 10s. Hotwire probe calibration was conducted against the pitot-static tube. Temperature measurements during the calibration showed fluctuations within \( \pm 0.5^\circ C \), avoiding bias errors due to thermal drift of the voltage signal.

### 2.3.4 Force Balance

The test airfoil with an alula is mounted to an ATI Gamma 6-axis force/torque sensor with amplified, high-signal-to-noise ratio signal output and a sensitivity of 1/160 N. The sensor axes are aligned with the wind tunnel flow direction and is fixed to a precision rotary table. The wing AoA is set through a control logic in 1° increments, details are provided in Section 2.3.5. The airfoil is mounted to an adapter plate, which is firmly attached to the load sensor, which is part of the rotary table assembly, see Figure 14). The desired wing angle of attack is set by rotating the rotary table, sensor and wing with respect to the freestream flow direction. The airfoil is free to rotate around a pivot point close to the airfoil quarter chord location, \( c/4 \), and is aligned with the centerline of the adapter plate.

In order to decrease the force and moment loading on the axis of the sensor registering lift force, the airfoil section is supported by a reaction plate mounted to floor of the test section. The drag force axis is unsupported due to the low drag values in the tested conditions. A spring pin, threaded in the wing at \( x/c = 0.25 \) is used as contact point between the airfoil and reaction plate. The pin is aligned with the walls of the plate, such that not to apply forces when rotating the airfoil in no flow conditions. The system is best described as a statically determined propped cantilever beam. The reaction force at the sensor plate, \( R_1 \) is calculated via:
Figure 14: Detailed schematic of the experimental setup. Hot-wire probe is located immediately after the TE and traverses along the span as well as in the direction perpendicular to the axis passing through the $c/4$.

$$R_1 = \frac{5L}{8}$$ (3)

where, $L$ is the integrated lift force and $b$ is the wing span. The generated lift by the wing can then be solved for, $L = \frac{8R_1}{5}$.

### 2.3.5 Precision Rotary Table

For the purpose of wind tunnel testing, a precision rotary table is integrated into an assembly that would fit in a circular opening at the test section ceiling. The table serves three goals: 1) affix the test specimen to the wind tunnel wall 2) provide accurate and repeatable rotation (Angle of Attack) and 3) measure Force/Torque values. The assembly is designed to accept the ATI Gamma Force/Torque sensor, as well as any other instrumentation necessary. Figure 15 shows the rotary table in fully assembled (a) and disassembled (b) states. The system is controlled by an Arduino Uno R3 control board, a Bi-polar Micro-stepping stepper motor.
and driver and 24V, 300W DC power supply. The gear ratio between the stepper motor and the rotating platform is 1:72, the NEMA 17 stepper motor rotates in 1.8° increments, and the stepper motor driver is set to a minimum of 2 microsteps per step, producing angular resolution of ±0.0125°. The system is rated at 100 arc-second accuracy and 1 arc-second repeatability (www.velmex.com).

### 2.3.6 Hot-wire Traversing System

In order to position the hot-wire probe at the desired location in a repeatable manner, a 3-dimensional positioning system is designed. A schematic and a photo of the assembly are shown in Figure 16 for clarity. The position table is comprised of 2 CNC (computer numeric control) controlled axes, i.e. the Z and X axes, see Figure 16(a) for axis orientation. The axis in the flow direction is not automatic and is manually operated. Both CNC axes use a lead screw to translate the stepper motor shaft rotation to linear motion. The stepper motor used was a NEMA 23 with 1.8°/increment (2 microsteps per increment) and is connected to a lead screw with 0.1“ linear advance/turn, producing 0.000025” linear resolution. The system is rated to 0.003“ straight line accuracy and 0.0001” repeatability (www.velmex.com).
Figure 16: (a) CAD Isometric representation and (b) physical experimental setup of hot-wire probe traversing system. The motion axes allow for probe translation along the spanwise and transverse to the flow direction

2.4 PIV Experimental Setup

In order to isolate any tip vortex interactions with the alula wake, the experiment was designed as a 2D airfoil configuration, similar to the wake and BL measurements conducted previously. With positional constraints on the location of the PIV laser and camera, the airfoil is oriented to span the long side of the wind tunnel. With target $Re$ of 100,000 and 135,000 and minimum size requirements for the alula-wing ratio, the aerodynamic forces from full span wing ($b = 90$ cm) would oversaturate the force sensor. To mitigate this limitation, a splitter plate configuration is designed, allowing for span reduction to a desired wing surface area. Shown in Figure 17, the wing spans from the wind tunnel wall to the splitter plate. The airfoil is attached to the force sensor through an adapter plate and the AoA is controlled by a precision rotary table as described in detail by Section 2.3.5. The airfoil is simply supported at the splitter plate end by a pin and bearing allowing for unrestricted rotation. Due to the mechanics of the setup, there is a correction factor in deriving lift and drag forces, as previously described in Section 2.3.4.

The splitter plate is immersed in the flow away from the walls, resulting in the development of a fresh boundary layer forming from the leading edge of each plate. In addition to
reduction in the test section and fresh boundary layer generation, using splitter plates allows for placement of support members in the wind tunnel test section without disturbing the flow over the airfoil. The benefits of using splitter plates come with some considerations and restrictions that have to be carefully examined. There are three main effects, which can affect the flow measurements: a) spillage effect, b) entrainment or side-wall blockage effect and c) thick-plate blockage effect. The presence of the airfoil and specifically its wake cause spillage of air between the wind tunnel walls and the splitter plates. One remedy is to add dummy models between the plates and wind-tunnel walls in an effort to balance the spillage of air. In a similar fashion, adding movable flaps to the trailing edge (TE) of the splitter plates alleviates the spillage effect. However, dummy models tend to stall earlier than the airfoil model, making accurate measurement of freestream velocity challenging. TE flaps, require dynamic pressure measurements between wind-tunnel walls and splitter plates in addition to the measurements of the test section, requiring more complex instrumentation.

Flow measurement uncertainties that spillage, entrainment and blockage effects cause cannot be quantitatively described, which makes it impossible to calibrate the flow in the test section to the upstream flow. This requires a direct measurement of flow properties between the splitter plates in close proximity of the test specimen. One complication of this approach is that the circulation created from the test airfoil will affect the velocity measurement. Since the aerodynamic coefficients are normalized by the dynamic pressure, correcting the velocity measurement is important for obtaining high experimental result fidelity. The effect of the pitot-tube proximity to the airfoil is evaluated and the dynamic pressure increment reported. The details of the used methodology is given by Giguere and Selig [9]. The maximum found error in Reynolds number has been found to be 0.5%.

2.4.1 PIV Instrumentation

A planar particle image velocimetry (PIV) experimental method is used to validate and quantify the flow field around a 2D airfoil in the presence of the alula device. The PIV system provides high-resolution 2D velocity fields on the upper surface of the test airfoil. The air flow is seeded with 1 μm olive oil droplets generated by 5 Laskin nozzles, placed
upstream of the wind tunnel inlet section. A 250 mJ/pulse double-pulsed laser (Quantel) was used to illuminate the field of view (FOV) of an 11 MP(4000 x 2672 pixel) 12-bit frame-straddle CCD camera. The laser sheet was 1 mm thick, and the FOV covered a region defined by $x/c = [0, 2.0]$ in the streamwise direction and $y/c = [0, 1.4]$ in the lift direction, see Figure 17. A total of four thousand image pairs were collected for each of the four test setups at a frequency of 1 Hz. The collected image pairs were analyzed by the software package Insight 4G (TSI), using a recursive cross-correlation method. The interrogation window was 24 x 24 pixels with 50% overlap, resulting in a final vector grid spacing $\Delta x = \Delta y = 0.9$ mm.

(a) Splitter plate was located close to midsection of the wind tunnel test section and the pitot tube was positioned upstream of the airfoil at a distance $x/c = 2.0$

(b) The laser sheet illuminates the oil particles in the flow through the glass opening in the wind tunnel test section and the pitot tube was positioned close to the wind tunnel floor.

Figure 17: PIV experimental setup with the test airfoil fixed to the splitter plate and the laser sheet on. The splitter plate is made of clear acrylic sheet allowing the CCD camera to capture the flow field.

The wind tunnel floor is glass and was used as the PIV laser sheet entry as opposed to the Acrylic side walls as seen in Figure 17. This is done to avoid excessive light scattering, potentially with detrimental effect on the particle illumination. The wing is supported on one side by the Velmex rotary table used to support the wing and provide precise incidence angle positioning and by the splitter plate on the other. To ensure frictionless rotation the wing is affixed to a circular adapter, allowed to rotate within the splitter plate. In Figure
the resulting splitter plate light defect is visualized on one of the 4000 RAW PIV image pairs.

![Image](image.png)

**Figure 18:** (a) PIV experimental setup isometric picture showing the location of the pitot tube, test specimen and the support adapter plate. The support adapter plate causes a light defect. (b) A single image from the collected 4000 PIV image pairs showing the lighting defect caused by the wing support structure, the test airfoil, the coordinate system and the size of the field of view. The image axes are rotated with positive lift in the +y direction for ease of results interpretation.

### 2.4.2 Wing and Alula Test Specimen

In order to test the same conditions as in the wake and boundary layer experiments, the test wing and alula airfoils are the same, i.e. S1223 and NACA 22 respectively, as detailed in Section 2.4.2. Due to the splitter plate configuration and limitations to the PIV resolution the wing and alula chord lengths were increased. The modified wing chord length was $c = 120$ mm and alula chord length was $c_{a_{\text{max}}} = 35$ mm. Through flow similarity $Re = 100,000$ and $135,000$ produce freestream mean flow velocities of $12.9 \text{ ms}^{-1}$ and $17.5 \text{ ms}^{-1}$ respectively.

### 2.4.3 PIV Experimental Test Matrix

The PIV test matrix was designed to evaluate the effect of the alula device on the airfoil flowfield. From the hot-wire boundary layer profile analysis in Section 3.1 at deep stall
Table 4: PIV test matrix. Tests were conducted at alula outboard spanwise location.

<table>
<thead>
<tr>
<th></th>
<th>Re = 100,000</th>
<th></th>
<th>Re = 135,000</th>
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<tr>
<td></td>
<td>β°</td>
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<td>0</td>
<td>10</td>
</tr>
<tr>
<td>α°</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

conditions α = 18°, alula angle β = −10° shows greatest effect in modifying the airfoil BL. Thus due to the resource intensive nature of PIV measurements the test matrix is setup to collect data as described in Table 4.
3 Results and Discussion

3.1 Hot-wire and Force Transducer Results

The effect of an alula-like leading edge device on the performance of a high-lift, low Re airfoil, the S1223, is evaluated. Three AoA conditions, $\alpha = 4^\circ$, $\alpha = 10^\circ$ and $\alpha = 18^\circ$ were tested in a systematic experimental approach at two wind tunnel freestream velocities: $Re = 1.0 \times 10^5$ and $Re = 1.35 \times 10^5$. In addition, three levels of alula deflection angles, $\gamma = 4^\circ, 13^\circ, 22^\circ$, and five levels of alula AoA, $\beta = -10^\circ, -5^\circ, 0^\circ, 5^\circ, 10^\circ$ are considered to understand the effect of the alula morphological parameters on the aerodynamics. $C_l$ for each wing AoA and alula configurations is recorded by the 6-axis force transducer and wake profile data from the hot-wire probe are presented. The hot-wire results, in the form of a wake velocity profile and turbulence intensity levels, are used to explain the differences observed in the lift generated by each configuration.

3.1.1 Boundary Layer Velocity Profiles, $Re = 1.0 \times 10^5$

Figure 19 shows the lift coefficient, $C_l$, at different alula tip deflection angles and AoA. At $Re = 1.0 \times 10^5$, the $C_l - \alpha$ curve for the S1223 has a sharp transition to stall conditions at $\alpha = \sim 7^\circ$ [25]. Figure 19(a) indicates that, at prior to stall conditions ($\alpha = 4^\circ$), no alula configurations show an increase in $C_l$, suggesting that the alula is a device designed to deploy in post stall conditions. The response parameter, $C_l$, is sensitive to an increase in alula deflection angle, $\gamma$. An increase in alula deflection angle from $\gamma = 4^\circ$ to $22^\circ$ shows an increase in $C_l$ values, Figure 19(b). While in this test condition, $\gamma$ has no appreciable effect on the lift. The $C_l$ versus $\beta$ plot of Figure 19(b) shows that the best $C_l$ value is achieved at the lowest alula AoA. At $\alpha = 18^\circ$ (Figure 19(c)), $\gamma$ shows a stronger correlation with $C_l$, with $\gamma = 22^\circ$ showing consistently better results.

Figure 20 (a) and (b) show results from the wake profile velocity measurements and turbulence levels at $\beta = 0^\circ$ and $-10^\circ$. Both tests are conducted at $\gamma = 13^\circ$ and $\alpha = 10^\circ$. The results are compared to the baseline configuration. The positive effect of the alula (i.e.
Figure 19: $C_l$ results from alula test parameters variations and their interactions at $Re = 1.0 \times 10^5$. (a) $\alpha = 4^\circ$ (b) $\alpha = 10^\circ$ (c) $\alpha = 18^\circ$. $C_l$ values are indicated with (- -).

The reduction in wake deficit) is only observed in the alula root region, $z = +20$ mm, and resembles that of a slat effect by decreasing the size of the separation region significantly.
Figure 20: (a) Hot-wire probe wake survey velocity profiles comparing alula configurations with the baseline airfoil and (b) Turbulence intensity levels, $I_n$. The alula effect is primarily seen at the inboard section of the alula, $z = +20$ mm with $\beta = 0^\circ$ producing the weakest flow velocity deficit. Turbulence intensity levels follow similar trend with $\beta = 0^\circ$ having the nearest to the wing surface shear layer. $\alpha = 10^\circ$, $\gamma = 13^\circ$, $Re = 1.0 \times 10^5$. 
However, at $z = 0$ and $-20\text{mm}$, there is no strong tip vortex effect the near surface wing BL, and the wake profile is unchanged or widened. The wake size can also be inferred from Figure 20 (b), which represents the flow turbulence intensity levels, $I_n$. The increase in turbulence levels is associated with the shear layer that exists between the high velocity free stream and the highly mixed, reversed flow wake. Figure 20(b) shows that there is a shift in the shear layer location and size with respect to the span-wise location. Due to the presence of the alula device at the inboard section ($z = +20 \text{ mm}$), the wake region shear layer is observed to diminish at $y/c = 0.15, 0.2$ and $0.32$ for $\beta = 0^\circ, -10^\circ$ and the baseline, respectively. In contrast, beyond the alula tip ($z = -20 \text{ mm}$), the order is reversed with respect to $\beta$. The increased distance of the shear layer beyond the alula for all $\beta$ configurations can be explained by the higher physical location of the alula wing tip. The higher shear layer and thicker wake for $\beta = 0^\circ$ can be attributed to the alula tip vortex by the smaller wake velocity deficit in the alula root location (Figure 20 (a)).

At $\alpha = 18^\circ$, $\beta = -10^\circ$ has the best Bl velocity recovery (Figure 21(a)). This is expected because at higher wing AoA, lower alula angles perform better since the local flow conditions allow for attached BL and good circulation. The overlapping velocity profiles of the baseline case with those of $\beta = 0^\circ$, and $10^\circ$ indicate that the alula is not improving the flow condition and in fact it is stalled and therefore unable to modify the wake size and move the shear layer closer to the wing surface. These results confirm the observations made from the interactions between $\beta$ and $\gamma$ on Figure 19(c), i.e. at $\gamma = 13^\circ$, the lower alula angles produce the highest improvements in $C_l$. Small improvements are still observed with $\beta = 0^\circ$ and $10^\circ$ and may be attributed to the incremental lift that the alula surface produces at sub-optimal conditions.

3.1.2 Boundary Layer Velocity Profiles, $Re = 1.35 \times 10^5$

For a wing with cross sectional airfoil S1223 at $Re = 1.35 \times 10^5$, stall begins at $\alpha = 13^\circ$. Hence, at $\alpha = 4^\circ$, the trend is similar to that for $Re = 1.0 \times 10^5$ - the BL is attached and the alula has a mostly negative impact (Figure 22). With the exception of a slight improvement in $C_l$ for $\alpha = 4^\circ$ at $\beta = -5^\circ$ and $0^\circ$, the alula remains a poor choice for wing angles below that
Figure 21: (a) Hot-wire probe wake survey velocity deficit profiles, $U/U_\infty$, comparing alula configurations with the baseline airfoil and (b) Turbulence intensity levels, $I_n$. The alula effect is primarily seen at the inboard section of the alula, $z = +20$ mm with $\beta = -10^\circ$ producing the weakest flow velocity deficit. Turbulence intensity levels follow similar trend with $\beta = -10^\circ$ having the nearest to the wing surface, shear layer. $\alpha = 18^\circ$, $\gamma = 13^\circ$, $Re = 1.0 \times 10^5$. 
of the onset of stall. Figure 22(b) shows the effect of the alula morphological parameters on the lift coefficient at $\alpha = 10^\circ$. The effect of the alula is, again, adverse with relative improvements at $\beta > -5^\circ$ and $\gamma = 13^\circ$. At a wing AoA of $\alpha = 18^\circ$, Figure 22(c) show that $C_l$ improvements are observed at all alula configurations tested, which is indicative of the positive impact the alula has on the wing surface flow conditions.
Figure 22: $C_l$ results from alula test parameters variations and their interactions at $Re = 1.35 \times 10^5$. (a) $\alpha = 4^\circ$ (b) $\alpha = 10^\circ$ (c) $\alpha = 18^\circ$. Baseline $C_l$ values are indicated with (- -).
At AoA $\alpha = 10^\circ$, the velocity profiles (Figure 23 (a)) provide an explanation of the reduction in $C_l$ due to the presence of the alula. The BL inboard of the alula, $z = +20$ mm, is highly disturbed at both $\beta = -10^\circ$ and $10^\circ$. Similarly to the results at $Re = 1.0 \times 10^5$, at $Re = 1.35 \times 10^5$ only $\beta = 0^\circ$ shows a BL with minimal wake deficit and no negative impact on the velocity profile at the alula tip and outboard spanwise locations. Turbulence intensity plots (Figure 23 (b)) convey the size of the wake behind the alula configurations at $\beta = -10^\circ$ and $10^\circ$, extending the wake shear layer of the wing far beyond $y/c = 0.2$ (baseline).

At $\alpha = 18^\circ$ wake profile deficit is similar to $Re = 1.0 \times 10^5$, in that, for $\beta = -10^\circ$, the wake size is reduced the most at $z = 0$ mm and $z = -20$ mm, Figure 24. In the inboard section, $z = +20$ mm, the wake deficit appears to be negatively affected, suggesting that the alula slat effect is suppressed. In fact, at $z = +20$ mm BL flow velocity is reduced to a third of the freestream value, and the turbulence intensity levels are close to 30%, which is the highest among all alula configurations. At the alula tip location and at $\beta = -10^\circ$, much of the wake deficit is recovered in the near surface BL, which suggests delayed flow reversal. Moreover at 20 mm outboard of the alula tip ($b = -20$ mm), the wing surface BL continues to improve over baseline conditions.

3.1.3 Spectral Difference

Spectral decomposition is performed to get information about the prevalent turbulence structures in the wake of the airfoil at different $Re$, AoA and alula configurations. To highlight the differences in the turbulence energy cascade between $\beta = -10^\circ, 0^\circ, 10^\circ$ with the addition of an alula device, the spectral differences, $\Delta(f\Phi) = f\Phi_{alula} - f\Phi_{noalula}$, of several test configurations are shown in Figures 25 - 27. At the high velocity setting $Re = 1.35 \times 10^5$ velocity profiles showed significant reduction in the wake deficit. To further understand how the alula device relative incidence angle modifies the flow the three tested configurations are plotted in Figures 25, 26 and 27. The pre-multiplied spectral difference plotted is given by $\Delta(f\Phi) = f\Phi_{alula} - f\Phi_{noalula}$. Higher spectral difference values indicate added turbulence by the alula device presence in the flow. Alternating warmer and colder regions in the $y/c$ direction represent a shift of energy distribution through the boundary layer, normal to the
Figure 23: (a) Hot-wire probe wake survey velocity deficit profiles, $U/U_\infty$, comparing alula configurations with the baseline airfoil and (b) Turbulence intensity levels, $I_n$. The alula effect is primarily seen at the inboard section of the alula, $z = +20 \text{ mm}$ with $\beta = -10^\circ$ producing the weakest flow velocity deficit. Turbulence intensity levels follow similar trends with $\beta = -10^\circ$ having, the nearest to the wing surface, shear layer. $\alpha = 10^\circ$, $Re = 1.35 \times 10^5$.

Comparing the wake deficit and turbulence intensity plots in Figure 23 for $Re = 1.35 \times 10^5$ and $\alpha = 10^\circ$ with the spectral difference plots in Figures 25, 26 and 27, no significant addition of turbulence energy is registered with an alula device angle of $\beta = 0^\circ$. This confirms the hypothesis that at $\beta = 0^\circ$, the alula is operating in favorable local flow conditions. At
Figure 24: (a) Hot-wire probe wake survey velocity deficit profiles, $U/U_\infty$, comparing alula configurations with the baseline airfoil and (b) Turbulence intensity levels, $I_n$. The alula effect is primarily seen at the inboard section of the alula, $z = +20$ mm with $\beta = -10^\circ$ producing the weakest flow velocity deficit. Turbulence intensity levels follow similar trends with $\beta = -10^\circ$ having, the closest to the wing surface, shear layer. $\alpha = 18^\circ$, $Re = 1.35 \times 10^5$.

$\beta = -10^\circ$ and $\beta = 10^\circ$, Figure 25(a) and 25(a), the turbulence energy increase is relatively high, suggesting that the alula wing is stalled, either on the upper or lower surface. At the alula tip ($z = 0$ mm) the alula wing chord length is shorter, causing smaller impact on the turbulence levels as seen in Figure 25(b) and 27(b). At the outboard spanwise location, $z = -20$ mm, Figure 25(c), 26(c), and 27(c) there is no observable difference between the
wake profiles between alula configurations, which may be attributed to the weak circulation created by the alula. Furthermore, without a strong alula wing bound circulation, the influence zone from the tip vortex is smaller. The combination of lower flow velocity and the adverse pressure gradient over an airfoil at high AoA can explain the premature vortex breakdown. Thus, if $\beta$ is inappropriate for the local flow conditions and $\gamma$ is high, the distance between the alula tip and wing surface may be too large for a weak vortex in a strong adverse pressure gradient to positively affect the surface BL.

**Figure 25:** $Re = 1.35 \times 10^5 \alpha = 10^\circ, \beta = -10^\circ$.

**Figure 26:** $Re = 1.35 \times 10^5 \alpha = 10^\circ, \beta = 0^\circ$. 
To further highlight the changes imposed on the surface BL, Figure 28 compares $(f \Phi)$ at the inboard, alula tip, and outboard span-wise locations. The power spectra are taken at a location above the wing surface, namely $y/c = 0.075$. The location was selected because it is close to the center of the developed boundary layer. In Figures 25 - 27, the location $z = +20$ mm indicates the largest addition of turbulence energy into the wake of the airfoil. At $\beta = 0^\circ$ there is no shift of turbulent energy across the BL, pointing to the fact that the surface BL is not greatly affected. In Figure 28 both alula configurations that produce higher velocity deficits, $\beta = -10^\circ$ and $\beta = 10^\circ$, shift the power spectra towards lower frequencies. Thus, the alula has the ability to modulate the size of the shed eddies and their energy levels. This can explain the fact that at $Re = 1.35 \times 10^5$ and $\beta = 0^\circ$, the highest BL average velocity levels are observed, resulting in higher $C_l$, compared to the other device configurations.

Figure 27: $Re = 1.35 \times 10^5$ $\alpha = 10^\circ$, $\beta = 10^\circ$. 

(a) $Z = +20$ mm

(b) $Z = 0$ mm

(c) $Z = -20$ mm
3.2 PIV Results and Discussion

In section 3.1 it is shown that force balance measurements of the airfoil at $\alpha = 18^\circ$ and $\beta = -10^\circ$ produce higher $C_l$ values for both Re tested. Furthermore, point wake survey results indicate that the streamwise velocity deficit in the wake of the wing is reduced in the presence of the alula device. To further investigate the flow field a planar PIV experiment was conducted as described in Section 2.4.3. In this Section the mean flow field and turbulence levels induced by the airfoil with alula are compared with those of the baseline configuration.

3.2.1 Mean Velocity Fields

The mean velocity flow fields in the longitudinal $U$ and lateral $V$ directions are normalized by the freestream mean velocity $U_\infty$. Both components are shown with the purpose of providing a comprehensive understanding of the alula effect. $U$ and $V$ are time-averaged over the full 4000 image pairs collected at a frequency of 1 Hz (details can be found in Section 2.4.1). The turbulent kinetic energy $\text{TKE} = \frac{1}{2} \langle (u'^2 + v'^2) \rangle / U_\infty^2$ and kinematic shear stresses $-\langle uv \rangle / U_\infty^2$ help identify turbulent instabilities, flow reversal and separation locations. Here the $\langle \rangle$ represents temporal averaging and $u_i = u_i - U_i$ are the velocity fluctuations with respect
to the local mean flow $U_i$.

In Figure 29(a) the streamwise flow field of the baseline case at $Re = 1.0 \times 10^5$ shows a separated flow region starting at a location on the chord line $\sim x/c = 0.5$ with a distinct wake contraction followed by a rapid expansion. In contrast the wake behavior of $U/U_\infty$ in the case of the deployed alula device shows delayed separation location $\sim x/c = 0.6$ and a narrower wake with much reduced momentum deficit in $U$. In the lateral direction, the flow fields of the baseline and the alula configuration cases are displayed in Figures 29(c) and 29(d). The presence of the alula strongly influences the lateral velocity field by increasing the near surface $V$, over the full chord length of the airfoil. Streamwise velocity component $U$ shows no momentum loss over the upper surface, which leads to the conclusion that there is momentum transfer and deposit to the airfoil boundary layer, to a much larger extend as compared to the baseline case.
Figure 29: Streamwise $U/U_\infty$ and spanwise $V/U_\infty$ velocity distributions over the upper airfoil surface. a-b baseline configuration, c-d with alula device, $Re = 1.0 \times 10^5$, $\alpha = 18^\circ$ and $\beta = -10^\circ$.

At $Re = 1.35 \times 10^5$ the streamwise and lateral velocity flow components exhibit similar differences between the baseline case and the alula configuration, Figures 30(a) and 30(c). Velocity component in the lateral direction also exhibits higher levels with the alula deployed, adding to the wing surface boundary layer momentum.
Figure 30: streamwise $U/U_\infty$ and spanwise $V/U_\infty$ velocity distributions over the upper airfoil surface. a-b baseline configuration, c-d alula deflected. Dashed line tracks the light defect from wing support structure as described in 2. $Re = 1.35 \times 10^5$, $\alpha = 18^\circ$ and $\beta = -10^\circ$
3.2.2 Kinematic Shear Stresses and TKE

Figure 31 shows the normalized Reynolds stresses and turbulent kinetic energy plots at $Re = 1.0 \times 10^5$ and $\alpha = 18^\circ$. The S1223 airfoil is in its deep stall region at this AoA and a leading edge separation is observed. In Figure 31(b) the mean flow has negligible turbulence, which means that all of the turbulence generated is as a result of the separated flow. The wake region that shows the highest TKE extends to $x/c = 1.5$. The TKE in the wake of the alula configuration, Figure 31(d), also extends to $x/c = 1.5$ but has half the energy content as compared to the baseline. From Figure 31(d) the wake deficit size is reduced significantly when the alula device is deployed. Furthermore, shear stresses over the near surface of the wing indicate early transition to turbulence $\sim x/c = 0.25$ and flow reversal $\sim x/c = 0.4$ followed by separation $\sim x/c = 0.6$, near the leading edge. In contrast, in the case of the alula configuration flow reversal does not occur until $\sim x/c = 0.7$. The TKE and shear stress levels shown in Figure 31 show that the presence of an alula device modifies the airfoil BL and wake structure in a favorable manner, delaying flow reversal and reducing the size and intensity of the turbulent wake.
Figure 31: Reynolds stress $-\langle uv \rangle / U_\infty^2$ and TKE $\langle u^2 + v^2 \rangle / U_\infty^2$ velocity distributions over the upper airfoil surface. **a-b** baseline configuration, **c-d** alula deflected, $Re = 1.0 \times 10^5$, $\alpha = 18^\circ$ and $\beta = -10^\circ$.

Figure 32 compares the TKE and shear stress levels between the wing with the alula device deflected and baseline at $Re = 1.35 \times 10^5$ and $\alpha = 18^\circ$. Similarly to the $Re = 1.35 \times 10^5$ results the baseline case shows early turbulence transition and immediate flow reversal and separation at $\sim x/c = 0.1$. In TKE levels of the baseline results, Figure 32(b), the wake encompasses the entire airfoil chord length and is highly energetic. In comparison, the alula test case shows much lower levels of TKE in the wake and the wake deficit growth is less abrupt. In Figure 32(c) flow separation is delayed to $\sim x/c = 0.6$, which resulted in $\sim 15\%$
increase in $C_l$ (see Section ??). It should be noted that in Figure 32(c) and 32(d) the PIV velocity field shows a defect as a result from light scattering from the interface between the wing support structure and the splitter plate, as described in more detail in Section 2.4. The TKE and Reynolds stresses can still be evaluated because of the narrow affected region.

Figure 32: Reynolds stress $-\langle uv \rangle / U_\infty^2$ and TKE $\langle u'^2 + v'^2 \rangle / U_\infty^2$ velocity distributions over the upper airfoil surface. a-b baseline configuration, c-d alula deflected. Dashed line tracks the light defect from wing support structure as described in Section 2.4. $Re = 1.35 \times 10^5$, $\alpha = 18^\circ$ and $\beta = -10^\circ$.
3.3 Results Summary

The alula wing was designed to have close resemblance to the morphological parameters of an averaged alula feather structure from several birds. Design parameters believed to influence the aerodynamics of the LEAD-wing system are tested - alula angle of attack \( \beta \) and deflection angle \( \gamma \). In order to test the ability of LEAD to delay stall the wing angle of attack \( \alpha \) is varied from \( 0^\circ \) to deep stall conditions \( \alpha = 26^\circ \). Force balance measurements of the generated lift showed that the LEAD only improves the airfoil performance in stall conditions \( \alpha = 10, 18^\circ \) at \( Re = 1.0 \times 10^5 \) (stall occurs at 6-8\(^\circ\)). At \( Re = 1.35 \times 10^5 \) stall occurs later, thus LEAD improvements are shifted to \( \alpha = 18^\circ \) only. From the tested morphological parameters \( \gamma \) shows strongest positive effect on \( C_l \) with higher values consistently performing better. The effect of the alula angle of attack \( \beta \) on \( C_l \) is positive with negative values with \( \beta = -10^\circ \) to \(-5^\circ \) consistently outperforming all other tested angles.

Hot-wire wake velocity profile measurements further supported the previous findings. At stall conditions the airfoils with alula angle \( \beta = -10^\circ \) compresses the wake deficit zone, shifting the shear layer closer to the airfoil surface. Local flow conditions, flow angle and velocity, at the alula location are important for the proper operation of the LEAD wing, and as such, it is expected that at low \( \alpha \) the relative LEAD angle \( \beta \) must also be lowered. This is phenomenon is observed through the wake velocity profiles - at \( \alpha = 10^\circ \) the highest momentum BL is that of \( \beta = 0^\circ \), while at \( \alpha = 18^\circ \) most energetic is the BL with \( \beta = -10^\circ \).

Energy power spectrum of the wake is extracted from the high frequency velocity data gathered with the hot-wire probe. Analysis of the pre-multiplied spectral difference between baseline and LEAD test cases show that the device has the capacity to limit the BL reversal and separation evidenced by the shifted turbulence levels off the airfoil surface. Comparison between \( f\Phi \) power spectrum curves taken inside the BL at three \( \beta \) angles \( (Re = 1.35 \times 10^5, \alpha = 10^\circ) \) confirms that at \( \beta = 0^\circ \) the LEAD suppresses the eddy production across all frequencies. The same flow mechanics are observed in deep stall conditions \( \alpha = 18^\circ \), where at LEAD angle of \( \beta = -10^\circ \) exhibits similar turbulence generation suppression. This finding is in line with the hypothesis that the LEAD relative angle of attack \( \beta \) must be such that to
allow the device to operate favorably in the local flow conditions.

Full velocity vector fields are generated with a single plane PIV system at $Re = 1.35 \times 10^5$, $\alpha = 18^\circ$ and $\beta = -10^\circ$. Time-averaged mean velocities confirm that the wake momentum deficit is greatly reduced with the LEAD deployed compared to the baseline. TKE and Reynolds shear stresses show that transition to turbulence between the test cases is similar but flow separation is greatly reduced with the LEAD deployed.
4 Concluding Remarks

4.1 Summary of Work

Adaptable aerodynamic surfaces are observed in every biological organism that takes flight. Bio-inspiration has served the aircraft industry from its inception with the Wright Flyer. Every flying organism has adopted a number of deployable, morphing aerodynamic surfaces to extend its flight capabilities. To transfer birds’ abilities to take off in short distance, fly for extended periods of time, soar with minimal energy expenditure, perch and land softly and accurately, an artificial system must adopt such adaptable devices as the alula. In this work a leading edge alula-inspired device (LEAD) is tested in a wind tunnel to assess its aerodynamic properties based on a set of morphological parameters. Results from force measurements show that a LEAD has the ability to increase $C_l$ at post-stall angles of attack. Furthermore, through high-frequency velocity data and PIV measurements the effect of the LEAD can also be shown to modify the boundary layer of the upper surface of an airfoil in a favorable manner as to reduce the wake deficit region and delay flow reversal and separation.

Section 2 presented a bio-inspired technical approach towards building a LEAD. Morphological parameters from nature have been translated to laboratory setting through adjustable device parameters. Alula angle of attack $\beta$, relative to main wing surface, and deflection ratio $\gamma$, defined as the rotation of the alula tip around the alula root, were used as the variable input parameters to construct a wind tunnel aerodynamic test matrix. The used wing and alula airfoils are the S1223 and NACA 22 respectively, and are selected based on their geometrical and aerodynamic similarity to birds operating in the flight category of interest. A force transducer was used to evaluate the $\Delta C_l$ increment the LEAD introduced over the baseline wing. Boundary layer profile and wake deficit surveys of pre- and post-stall test conditions were collected using a high frequency single-wire hot-wire CTA. A planar PIV system was used to obtain high resolution 2D velocity fields at deep stall conditions, $\alpha = 18^\circ circ$ for both flow regimes, i.e. $Re = 1.0 \times 10^5$ and $Re = 1.35 \times 10^5$. 

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Force balance results of the wing and LEAD system confirmed the hypothesis that the alula is effective in improving the flow conditions over the airfoil in post stall regimes of operation. In the pre-stall, linear $C_l - \alpha$ range, the deployment of the alula has a negative effect on $C_l$. However, at both $Re$ tested the wing $C_l$ was shown to improve in the deep stall region, $\alpha = 18^\circ$. This is consistent with the deployment mechanism of the alula feather structure in nature [5]. Wake and BL profile surveys confirmed that the positive effect of the alula lies in its ability to re-energize the wing upper surface BL and reduce the wake mean velocity deficit. The PIV 2D velocity fields in deep stall conditions ($\alpha = 18^\circ$) at a span-wise location outboard of the alula tip, show higher mean wake velocity in the stream-wise and lateral directions, $U$ and $V$, when compared to the baseline configuration. This is indicative of the induced higher wing BL velocities by the alula wing tip trailing vortex system.

4.2 Future Recommendations

In this work a series of experimental approaches have been undertaken in order to better understand the effect of LEAD morphological parameters on the airfoil performance. In the course of the investigation several test methodologies have been identified to receive more attention in future iterations of this research topic. Firstly, force data collection should be improved to remove variability and reduce the error margin of the data. This is particularly important when the incremental changes expected fall in the order of magnitude of the aggregate error. Supplementary wake deficit analysis using a pitot tube may provide a more robust $C_d$ values. 

Certainly more data points are necessary for the hot-wire measurements to build a more comprehensive picture of the BL development in the streamwise direction. Better positional precision will allow for near surface probe placement, which will produce more complete boundary layer profiles. Similarly, higher number of PIV sheets at various spanwise locations would provide better understanding of how alula deflection angle influences the flow and to quantify the effect of the device on the spanflow and wake propagation.

A natural progression in the evaluation of the LEAD is conducting a three dimensional test
of the alula device system. The alula is naturally a 3D aerodynamic structure and the effect on a 3D wing would inevitably be different than those on a full span, 2D airfoil. In the 3D experimental setup, important set of morphological parameters will be introduced, i.e. alula device root location in spanwise direction and device-to-wing span ratio. These variables along with $\beta$ and $\gamma$ will interact with the wing tip vortex structure to produce a coherent LEAD-wing system response.

The LEAD design has been inspired by nature systems with highly complicated functionality. The alula on a bird’s wing is highly adaptive and constantly responds to the flow conditions. In order to approach the true nature of operation of such a device an adaptive, flexible alula-like structure should be investigated. The flow near the leading edge of a wing has strong pressure gradients that can be utilized for passive deployment of such a device, making control mechanisms unnecessary. Designing a flexible alula device would also provide better understanding of the fluid-structure interaction in a dynamic way.
References


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[29] Weick, F. E., and Platt, R. C. Wind-tunnel tests on model wing with fowler flap and specially developed leading-edge slot.
Appendix A  \( Re = 100,000 \) PIV Pre-multiplied Contours

\[ Re = 100,000 \]

Figure 33: \( Re = 1.00 \times 10^5 \alpha = 4^\circ, \beta = -10^\circ \).

Figure 34: \( Re = 1.35 \times 10^5 \alpha = 10^\circ, \beta = 0^\circ \).

Figure 35: \( Re = 1.00 \times 10^5 \alpha = 4^\circ, \beta = -10^\circ \).
Figure 36: \( \text{Re} = 1.35 \times 10^5 \alpha = 10^\circ, \beta = 0^\circ. \)

Figure 37: \( \text{Re} = 1.35 \times 10^5 \alpha = 10^\circ, \beta = 10^\circ. \)
Appendix B \( Re = 135,000 \) PIV Pre-multiplied Contours

Figure 38: \( Re = 1.35 \times 10^5 \alpha = 10^\circ, \beta = -10^\circ \).

Figure 39: \( Re = 1.35 \times 10^5 \alpha = 10^\circ, \beta = 0^\circ \).

Figure 40: \( Re = 1.35 \times 10^5 \alpha = 10^\circ, \beta = 10^\circ \).