Low-Reynolds-Number Effects in Passive Stall Control Using Sinusoidal Leading Edges

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The objective of the present work is to investigate the application of a sinusoidal leading edge to the design of micro air vehicles. Wind-tunnel tests of wings with low aspect ratios of 1 and 1.5, rectangular planforms, and five distinct leading edges [four sinusoidal leading edges and one baseline (straight) leading edge for each aspect ratio] have been conducted. The Reynolds numbers of 70,000 and 140,000 have been analyzed. For the higher Reynolds number, a proper combination of amplitude and wavelength can lead to a substantial increase in lift for angles of attack greater than the baseline stall angle. Maximum lift coefficient gains of the order of 45% were achieved by combining both large amplitude and large wavelength. At the lower Reynolds number, the benefits can be extended to low angles of attack, leading to a dramatic increase in the range of operation. The results depend strongly on the aspect ratio.

**Nomenclature**

\[
\begin{align*}
A &= \text{protuberance amplitude, mm} \\
AR &= \text{aspect ratio, } b^2/s \\
b &= \text{wingspan, mm} \\
c &= \text{chord, mm} \\
C_D &= \text{drag coefficient, } D/(\tfrac{1}{2} \rho V_c^2 S) \\
C_L &= \text{lift coefficient, } L/(\tfrac{1}{2} \rho V_c^2 S) \\
D &= \text{drag force, N} \\
L &= \text{lift force, N} \\
Re &= \text{Reynolds number, } \rho V_c S/\mu \\
S &= \text{wing area, mm}^2 \\
V_\infty &= \text{freestream velocity, m/s} \\
\alpha &= \text{angle of attack, deg} \\
\lambda &= \text{protuberance wavelength, mm} \\
\mu &= \text{viscosity, kg/ms} \\
\rho &= \text{air density, kg/m}^3
\end{align*}
\]

**I. Introduction**

**T**he interest in micro air vehicles (MAVs) has grown exponentially in recent years motivated by the increasing capability in miniaturizing the avionics. Equipped with small video cameras, transmitters, and sensors, MAVs are perfect candidates for special limited-duration military and civil missions, which may include real-time images of battle areas; and monitoring of forest natural disaster areas; and real-time images of battlefronts. MAVs can perform admirable turning maneuvers to catch prey [4]. Its capability in miniaturizing the avionics, small weight, and wind gusts presents numerous challenges [3].

The use of classical methods such as synthetic jets, and blowing or suction, to control stall and increase the range of operation may in certain cases be too energy-consuming for use in MAVs, and the weight penalty on a flight vehicle is prohibitive. Here, we investigate the application of a passive method inspired by humpback whale (Megaptera novaeangliae) pectoral flippers at moderate to low Reynolds numbers. The humpback whale is extremely agile, and it can perform admirable turning maneuvers to catch prey [4]. Its pectoral flippers exhibit high aspect ratios (close to 6), being the longest among the cetaceans, and present an elliptical planform. However, its most notable feature is the unusual leading edge, made up of several protuberances (tubercles), which gives it an appearance resembling a sinusoidal pattern [5]. Figure 1 shows a photograph of the humpback whale and its pectoral flipper. The first wind-tunnel experiments conducted by Miklosovic et al. [6] used a scale model of an idealized humpback whale flipper. They showed a delay in the stall angle from about 12 to 16 deg while increasing the maximum lift and reducing the drag over a portion of the operational envelope. The investigated Reynolds number was about 500,000, estimated to be half of the value of an adult humpback whale. Subsequently, Stanway [7] tested a similar scale model at Reynolds numbers between 45,000 and 120,000. He also reported a delay in the stall angle; however, increases in maximum lift were found for the higher Reynolds number only. Particle image velocimetry flow visualization suggested that two longitudinal counter-rotative vortices are formed at each protuberance, in a manner similar to the leading-edge vortices of a delta wing, by energizing the flow these enabled stall delay. Employing a different approach, Miklosovic et al. [8] (at \( Re \approx 275,000 \)) and Johari et al. [9] (at \( Re \approx 183,000 \)) tested infinite models in order to study the fundamental nature of the resulting flow from the presence of protuberances. Their results were substantially different from those obtained by others in finite scale models. An overall increase in drag was found, and the models with a sinusoidal leading edge were observed to stall first. However, the stall behavior was improved (i.e., it became more gradual) and the lift coefficients were still higher beyond the point of stall of the baseline model (i.e., without tubercles). Tuft visualization [9] showed that the flow separated first at the troughs between the adjacent protuberances while it was kept attached over the peaks at angles of attack higher than that of baseline model stall. Another interesting finding from Johari et al. was that the amplitude of the protuberances had a much greater effect on the results than its wavelength.

More recently, Pedro and Kobayashi [10] used a detached eddy simulation formulation to numerically simulate the experience of Miklosovic et al. [6]. They concluded that the longitudinal vortices

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not only delayed the trailing-edge separation taking place in the inboard section, where the local Reynolds number was higher \((Re > 500,000)\), but also prevented the propagation of the leading-edge separation occurring in the outboard section, where the local Reynolds number was lower \((Re < 200,000)\), from moving toward the root.

The primary goal of this study is to investigate the applicability of this solution for stall control to the design of MAVs. Normally, in the development of these vehicles, the wingspan is a size constraint, so low-aspect-ratio (LAR) wings provide the largest wing area for higher lift. Accordingly, and aiming to achieve the proposed objective, we use a combination of low-Reynolds-number and LAR wings with different leading-edge (sinusoidal) protuberances. The study is based on the direct measurement of the aerodynamic characteristics of the wings in a wind tunnel, complemented with smoke flow visualizations.

II. Experimental Apparatus

A. Wing Model Configuration

Despite its large maximum thickness (17% of the chord length), the NASA LS(1)-0417 profile (Fig. 2) was chosen for this study because it has been designed with a large leading-edge radius in order to flatten the peak in pressure coefficient in the nose region, thus discouraging flow separation and presenting a predictable, docile stall behavior [11]. Although thick airfoils are seldom used on MAV wings, the extra streamlined volume resulting from this choice may prove to be useful to host electronics without generating additional component drag.

Ten rectangular wings based on the aforementioned profile were computer numerical control machined from Duralumin blocks to ensure global accuracy of the airfoil sections and hand polished. The surface finish quality, less than 1 \(\mu\)m rms in roughness height, was measured with a Mitutoyo SJ-201 profilometer. The models have a mean chord length of 232 mm, and they can be divided in two sets according to their aspect ratio of 1 or 1.5. Each set is formed by the baseline model and four models with a sinusoidal leading edge, always keeping a constant wing planform area. To define the sine wave, the amplitudes \(A\) of 0.06\(c\) and 0.12\(c\) were chosen together with two wavelengths \(\lambda\) of 0.25\(c\) and 0.50\(c\). The selected values were inspired by previous investigations [9] and fall within the range of values associated with humpback whale pectoral flippers. Figure 3 illustrates the set of wings with an aspect ratio of 1.5. The models have been labeled as follows: the first characters define the type of model (“B” for the baseline model and “S” for a sinusoidal model) and the aspect ratio; the last characters, separated from the prefix by a dash and used for the sinusoidal models only, refer to its amplitude.
Table 1 Wing model dimensions

<table>
<thead>
<tr>
<th>Wing</th>
<th>C, mm</th>
<th>b, mm</th>
<th>AR</th>
<th>A, mm</th>
<th>λ, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>232</td>
<td>232</td>
<td>1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S1-L1</td>
<td>232</td>
<td>232</td>
<td>0.12</td>
<td>0.50</td>
<td>—</td>
</tr>
<tr>
<td>S1-L2</td>
<td>232</td>
<td>232</td>
<td>0.12</td>
<td>0.25</td>
<td>—</td>
</tr>
<tr>
<td>S1-S1</td>
<td>232</td>
<td>232</td>
<td>0.06</td>
<td>0.50</td>
<td>—</td>
</tr>
<tr>
<td>S1-S2</td>
<td>232</td>
<td>232</td>
<td>0.06</td>
<td>0.25</td>
<td>—</td>
</tr>
<tr>
<td>B1.5</td>
<td>232</td>
<td>348</td>
<td>1.5</td>
<td>0.12</td>
<td>0.50</td>
</tr>
<tr>
<td>S1-LL</td>
<td>232</td>
<td>348</td>
<td>1.5</td>
<td>0.12</td>
<td>0.50</td>
</tr>
<tr>
<td>S1-LS</td>
<td>232</td>
<td>348</td>
<td>1.5</td>
<td>0.12</td>
<td>0.25</td>
</tr>
<tr>
<td>S1-SS</td>
<td>232</td>
<td>348</td>
<td>1.5</td>
<td>0.06</td>
<td>0.50</td>
</tr>
<tr>
<td>S1-SS</td>
<td>232</td>
<td>348</td>
<td>1.5</td>
<td>0.06</td>
<td>0.25</td>
</tr>
</tbody>
</table>

(“L” standing for large amplitude, i.e., 0.12c, and “S” standing for small amplitude, i.e., 0.06c) and the wavelength (analogously, “L” for 0.5c and “S” for 0.25c). Table 1 lists the dimensions and other geometric parameters for the wing models used in this investigation. For simplicity, the models with and without protuberances along the leading edge are termed sinusoidal models and baseline models, respectively.

B. Wind Tunnel and Instrumentation

The experiments were performed in the open-circuit wind tunnel of the Department of Mechanical Engineering at Instituto Superior Técnico (Fig. 4). This wind tunnel operates in the low-speed (incompressible) flow regime using a blower installed at the inlet, up to a maximum speed of 10 m/s. Tests can be performed in the free jet or in a test section with a rectangular cross-sectional area of 1.35 × 0.8 m. Since the present study embraces the three-dimensional flow developing around the wing models, we have chosen to operate in free jet mode, aiming to reduce the need for wind-tunnel corrections due to blockage. The test section is preceded by honeycombs, screens, and a 3:1 contraction ratio to minimize the nonuniformity and the turbulence level of the undisturbed stream. Over the range of operating speeds used, the maximum freestream turbulence intensity is about 0.2%.

The aerodynamic forces (and moments) are transmitted to a six-component Schenck compact balance through a single-strut model support. The values measured by the load cells are acquired using a PREMA 5000 digital multimeter of six half-digits, which communicates with the host computer using the general purpose interface bus protocol. Scan rates of five channels per second can be executed with this system.

C. Experimental Procedures and Uncertainties

The experiments were conducted at two Reynolds numbers of 70,000 and 140,000, hereinafter termed as the low-Reynolds-number regime and the moderate Reynolds number regime, respectively. As the present work focused on the stall behavior displayed at positive incidences only, the angle of attack was varied from α = 0 deg to α = 30 deg. After this point, the wings were brought back to α = 0 deg to check if hysteresis was present. For each angle of attack, approximately 15 to 30 samples were acquired to form the average values of $C_L$ and $C_D$. Flow visualization tests were conducted for the B1.5 and S1.5-LL models at various incidences, using upstream smoke injection from a Safex 2001 fog generator with probe NS 1 (Dantec, Denmark) and a laser light sheet to illuminate the semispan plan. Still images were captured during the tests employing a Sony DSLR-A200 digital camera.

Wind-tunnel corrections (mainly for weight tares, load component interactions, and eventually wall corrections) were applied via Schenck proprietary software customized for our facility. A dedicated study for the models and operating conditions used here also allowed us to further correct the data with respect to model mount interactions.

Aiming to predict the overall 95% confidence limits for $C_L$ and $C_D$, we followed the procedure suggested by Coleman and Steele [12]. To estimate the precision uncertainties, the standard error for the mean force coefficients at each angle of attack was calculated and multiplied by the two-tailed t value ($t = 2$) used for a $t$ distribution and a number of readings (samples) greater than 10. These were combined with the estimates of the bias errors to predict the overall 95% confidence limits. Percentage uncertainties in $C_L$ are on the order of 4% for the moderate Reynolds numbers and 5% for the low Reynolds numbers. Uncertainties in $C_D$ are significantly larger, especially for the low Reynolds number and lower aspect ratio, where these may be twice as large due to the small magnitude of the measured forces. For this reason, the results presented here and the subsequent discussion are essentially based on the lift coefficient variations with angle of attack. The uncertainty in the angle of attack is estimated to be of the order of 0.2 deg.

III. Results

In this section, we start by presenting the results at a moderate Reynolds number ($Re = 140,000$): first for the wings of aspect ratio 1, and next for the wings of aspect ratio 1.5. Then, the results are discussed and compared. The procedure is subsequently repeated for results at a low Reynolds number ($Re = 70,000$).

A. Moderate Reynolds Number

1. Wings with Aspect Ratio of 1

Figure 5 shows the lift coefficient variation with angle of attack for wing models of $AR = 1$. The baseline model $C_L$ increases continuously at an approximately constant rate up to $\alpha = 21$ deg, beyond which it is slightly reduced (stalled). However, after this point, further increases in incidence still lead to larger lift values. The maximum $C_L$ of 0.79 is only reached at the maximum angle of attack tested ($\alpha = 30$ deg) and is approximately 13% higher than the value at the stall point. For $\alpha = 20$ deg, the $C_L$ behavior of all sinusoidal models is similar to that of the baseline model, despite the lower value of the slope $dC_L/da$, which ultimately introduces a penalization in lift coefficient. Still, these models show more favorable stall characteristics. The S1-LS model (the one differing more from the baseline leading-edge geometry) is the first to stall at $\alpha = 20$ deg, but it exhibits a more gradual and smoother stall than the baseline.

![Fig. 4 Schematic representation of the experimental setup (dimensions in centimeters). Wing model, support strut, and compact balance are not to scale.](image-url)
model. The S1-SL model (the one that deviates less from the baseline leading-edge geometry) stalls at a much higher angle of attack, $\alpha = 27$ deg. The remaining two sinusoidal models do not stall within the tested range. In the poststall regime, the most prominent feature is the penalization in lift introduced by the S1-LS model. On the other hand, the S1-LL model shows consistent gains in this regime but nonetheless, they are very small to be considered relevant.

Table 2 lists the principal aerodynamic characteristics of this set, namely, the lift coefficient at zero incidence $C_{L,0}$, the maximum $C_L$, the angle of maximum $C_L$, and stall angle.

### Table 2 Aerodynamic characteristics of the wings with $AR = 1$ at $Re = 140,000$

<table>
<thead>
<tr>
<th>Wing</th>
<th>$C_{L,0}$</th>
<th>$C_L$</th>
<th>$\alpha_{C_{L,0}}$, deg</th>
<th>$\alpha_{\text{stall}}$, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.120</td>
<td>0.79</td>
<td>30</td>
<td>21</td>
</tr>
<tr>
<td>S1-LL</td>
<td>0.142</td>
<td>0.82</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>S1-SL</td>
<td>0.136</td>
<td>0.75</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>S1-SS</td>
<td>0.140</td>
<td>0.79</td>
<td>30</td>
<td>27</td>
</tr>
</tbody>
</table>

2. **Wings with Aspect Ratio of 1.5**

The data obtained for the wings with an aspect ratio of 1.5 are presented in Fig. 6. Again, the baseline model increases $C_L$ at an approximately constant rate up to the angle of stall ($\alpha = 19$ deg), where the maximum $C_L$ of 0.78 is reached. In this case, the stall is abrupt and severe. Flow visualization confirmed the occurrence of leading-edge stall. However, due to the very small height of the (prestall) separation bubble at this Reynolds number, we were unable to document it clearly; hence, the corresponding photo is not shown here. Further increases in angle of attack reduce the lift, but for $\alpha > 24$ deg, growth resumes. In addition, aerodynamic hysteresis was found to be present. The hysteresis loop can be observed in Fig. 7 for the angles of attack lying within the range $17 \leq \alpha \leq 20$ deg. This results in considerable variations in lift coefficient. For example, the lift coefficient at $\alpha = 18$ deg is increasing in the branch of the hysteresis loop was found to be 55% higher than its corresponding value in the decreasing branch.

The sinusoidal models present (average) lift slopes in the linear region roughly 10% lower than the baseline. Interestingly enough, it is possible to observe that the S1.5-SL model (the one departing less from the baseline leading-edge geometry) shows the highest slope among the sinusoidal models, while the others remain indistinguishable. All sinusoidal models stall before the baseline model.

### Table 3 Aerodynamic characteristics of the wings with $AR = 1.5$ at $Re = 140,000$

<table>
<thead>
<tr>
<th>Wing</th>
<th>$C_{L,0}$</th>
<th>$C_L$</th>
<th>$\alpha_{C_{L,0}}$, deg</th>
<th>$\alpha_{\text{stall}}$, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1.5</td>
<td>0.176</td>
<td>0.78</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>S1.5-LL</td>
<td>0.178</td>
<td>0.74</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>S1.5-SL</td>
<td>0.175</td>
<td>0.68</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>S1.5-SS</td>
<td>0.188</td>
<td>0.74</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>S1.5-SS</td>
<td>0.173</td>
<td>0.69</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

3. **Discussion**

It may be concluded that, for the wings with an aspect ratio of 1, there is no significant advantage in modifying the geometry of the leading edge, as differences were small. This is due to the absence of a true stall behavior in the baseline model; the lift is only reduced about 6% and, subsequently, the previous increase with incidence resumes. In fact, the lift coefficient of all wings was always seen increasing at high angles of attack. This trend can be typically found in LAR wings [13,14]; it is associated to the augmented intensity of low pressure on the upper surface of the wing as a consequence of the tip vortices. For LAR wings, these vortices can have a dominant effect in the aerodynamic characteristics at high angles of attack. Torres and Mueller [14] also showed, by means of flow visualization, that the tip vortices energize the flow near the wingtips, limiting the separation bubble to the inboard section of the wing. So, this prevalent effect may explain the fast recovery of the baseline model from stall and the continuous increase of lift for all models at high angles of attack. The lift coefficient of the S1.5-LL model normalized by the lift coefficient of the baseline model ($C_{L,\text{S1.5-LL}}/C_{L,\text{B1.5}}$) is plotted in Fig. 8, demonstrating the superiority of the baseline model in most of the investigated range of angles of attack.

On the other hand, if the aspect ratio of the wings increases, the impact of the tip vortices on the upper wing surface is expected to decrease. This is in consonance with the observation that the baseline model of aspect ratio 1.5 presents a completely distinct stall behavior. The abrupt and severe stall causes a reduction of the lift coefficient of 32% (from its maximum value). In the poststall regime, a proper combination of protuberances’ amplitude and wavelength (namely,
large amplitude and large wavelength) lead to significant improvements over the baseline model. The normalized lift coefficient of the S1.5-LL model is also plotted against angle of attack in Fig. 8 for comparison purposes. At this higher aspect ratio, maximum gains in of the order of 45% can be achieved with a maximum loss of about 20–25%.

The results obtained for the wings with a larger aspect ratio also show that both amplitude and wavelength play a major role in the behavior of the lift coefficient, especially at high angles of attack. For a two-dimensional experiment, the investigations made by Johari et al. [9] showed that the wavelength played a minor role. However, if we compare the data evolution of S1.5-SL and S1.5-SS, large differences can be appreciated in the poststall regime. We also noted that the lift slope at high angles of attack (approaching 30 deg) is comparable in both these two sinusoidal models and the baseline model. This may suggest that they share a common mechanism, which might be responsible for such correspondence. Concerning the baseline model, it appears reasonable to assume that successive increases in incidence would increase the pressure difference between suction and pressure sides, thus intensifying the tip vortices at a point that the trend of lift decrease would be reversed. After a certain threshold in angle of attack (here, approximately \( \alpha = 24 \) deg), the flow around the wing would be dominated by tip vortex structures and the lift would grow once more continuously. However, in the case of the sinusoidal models, an additional entity is shaping the lift curve, namely, the vortices generated by the leading-edge protuberances (allowing the \( C_L \) to remain at a higher level after stall), together with the tip vortices and the inevitable resulting interaction, which seem to be particularly favorable for the S1.5-LL model.

B. Low Reynolds Number

1. Wings with Aspect Ratio of 1

The evolutions of the lift coefficient with angle of attack for all the wings with aspect ratio 1 operating at low Reynolds numbers are presented in Fig. 2. It is clearly observed that the wing models with protuberances along the leading edge have the potential to generate large lift benefits across the range of angles of attack, especially in the range \( 0 \leq \alpha \leq 5 \) deg.

The baseline model \( C_L \) increases with an unmistakably variable growth rate up to the angle of stall, \( \alpha = 19 \) deg. Similar to the studies performed at moderate Reynolds numbers, lift values recover immediately after stall (with a reduction in \( C_L \), of only 5%), and the lift coefficient keeps increasing toward the maximum investigated angle of attack. The peak of 0.75 is 36% larger than the value at the stall angle.

The sinusoidal models show, in addition to the higher \( C_L \) at low angles of attack, a more linear evolution of the lift coefficient before the angle of stall of the baseline model. In line with previous results, the model with the large amplitude and large wavelength of the protuberances displays notable aerodynamic characteristics, and a minimal lift penalty with respect to the baseline model can only be found in the range \( 10 \leq \alpha \leq 15 \) deg. This is a consequence of the lower average slope in the prestall regime, but the superiority is nonetheless evident. The S1-LS model exhibits the lowest performance among the sinusoidal models, revealing the consistence of these data with that previously discussed.

Table 4 summarizes the aerodynamic characteristics obtained for this set of measurements.

2. Wings with Aspect Ratio of 1.5

The lift coefficient for the wings with aspect ratio 1.5 is plotted in Fig. 10 as a function of angle of attack. Again, the sinusoidal models show the potential to generate large lift benefits, most notably for \( 0 \leq \alpha \leq 5 \) deg and \( 17 \leq \alpha \leq 30 \) deg. Once more, the baseline model \( C_L \) is seen increasing in a nonlinear fashion up to the angle of stall at 16 deg, where the maximum \( C_L \) of 0.64 is reached. The abrupt

**Table 4 Aerodynamic characteristics of the wings with AR = 1 at Re = 70,000**

<table>
<thead>
<tr>
<th>Wing</th>
<th>( C_{L_{max}} )</th>
<th>( C_{L_{min}} )</th>
<th>( \alpha_{L_{max}} ), deg</th>
<th>( \alpha_{L_{shift}} ), deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>–0.007</td>
<td>0.75</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>S1-LL</td>
<td>0.143</td>
<td>0.82</td>
<td>30</td>
<td>—</td>
</tr>
<tr>
<td>S1-SL</td>
<td>0.121</td>
<td>0.70</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>S1-SS</td>
<td>0.093</td>
<td>0.77</td>
<td>30</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>0.130</td>
<td>0.76</td>
<td>30</td>
<td>—</td>
</tr>
</tbody>
</table>
stall causes a reduction in lift coefficient of approximately 32%. However, no aerodynamic hysteresis was found at this lower Reynolds number. A confirmation that stall was indeed abrupt was provided by the flow visualization portrayed in Figs. 11 and 12. Just before stall, a separation bubble is observed in the leading-edge region. After stall, this separation bubble has burst and the flow is completely separated over the upper surface of the wing. Then, values are seen increasing up to \( \alpha = 21 \text{ deg} \), where a further reduction takes place. For \( \alpha \geq 25\text{ deg} \), the evolution is quite similar to the one at the higher Reynolds number, previously depicted in Fig. 6.

The sinusoidal models present a lower (average) lift slope (although more constant) before the stall angle. The S1.5-LL shows the highest lift slope among the models with protuberances. The stall is more gradual and less severe, leading to an improved performance in the poststall regime. Whereas at the higher Reynolds numbers, all sinusoidal models stalled first, at low Reynolds numbers, only the S1.5-LL stalls before the baseline model, namely, at \( \alpha = 15 \text{ deg} \). In the poststall regime, the lift coefficient evolutions with angle of attack are identical to those obtained for the higher Reynolds number.

The aerodynamic characteristics for this set of measurements are listed in Table 5.

3. Discussion

In contrast with the conclusions drawn from the experiments carried out at moderate Reynolds numbers, the latter data indicate that, for wings with an aspect ratio of 1 operating at low Reynolds numbers, it is advantageous (in terms of lift coefficient) to use a sinusoidal leading edge. The lift force produced by the model with larger amplitude and larger wavelength protuberances is larger than that produced by the baseline throughout the whole range of angles of attack. In Fig. 13, the normalized lift coefficient of this model is plotted against the angle of attack for \( \alpha \geq 10 \text{ deg} \). The graph is restricted to \( \alpha \geq 10 \text{ deg} \) because of the large relative difference between the \( C_L \) values in both sets at low angles of attack (to be discussed next), which would otherwise preclude a proper representation of the data. The results for the higher Reynolds number are also plotted in Fig. 13 to enrich the analysis and better illustrate the differences between the two regimes. Maximum gains of the order of 25% in lift can be obtained for \( \alpha \geq 10 \text{ deg} \).

Based on the data presented before in Figs. 9 and 10, relative gains in lift at low angles of attack are expected to be much higher. Aiming to determine the cause of such drastic differences between the two investigated Reynolds number regimes, in Figs. 14 and 15, we plot the lift coefficient as a function of angle of attack at moderate and low Reynolds numbers for the baseline and S1-LL models, respectively. It can be seen that the reduction in Reynolds number leads to a substantial performance deterioration of the baseline model (particularly at low angles of attack), whereas the S1-LL model seems to be remarkably insensitive to the Reynolds number variation. Behind this unexpected behavior, we have identified a region of separated flow near the trailing edge of the baseline model operating at \( Re = 70,000 \), which is much smaller or even nonexistent in the sinusoidal models. This matter is later analyzed in more detail with the aid of flow visualization for the models with an aspect ratio of 1.5.

<table>
<thead>
<tr>
<th>Wing</th>
<th>( C_{L_{\text{max}}} )</th>
<th>( C_{L_{\text{max}}} )</th>
<th>( \alpha_{L_{\text{max}}} ), deg</th>
<th>( \alpha_{\text{stall}} ), deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1.5</td>
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<td>0.64</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
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<td>0.154</td>
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</tbody>
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**Fig. 10** \( C_L \) vs \( \alpha \) for the models with \( AR = 1.5 \) at \( Re = 70,000 \).

**Fig. 11** Flow visualization for the B1.5 model at \( \alpha = 16 \text{ deg} \). Note the approximate location of the separation point denoted by “S” and the wing section contour at the visualization plane.

**Fig. 12** Flow visualization for the B1.5 model at \( \alpha = 17 \text{ deg} \). Note the approximate location of the separation point denoted by “S” and the wing section contour at the visualization plane.

**Fig. 13** S1-LL lift values normalized by B1 lift values at \( Re = 70,000 \) and 140,000.
The performance deterioration of the baseline model with an aspect ratio of 1 also translates into a lower stall angle. Interestingly enough, the maximum $C_L$ is only reduced 5%, which may be associated to the higher average lift slope after the stall angle. Nevertheless, such behavior is likely to be a consequence of the increased coherence of the tip vortices at low Reynolds numbers [15].

For the wings with an aspect ratio of 1.5, the baseline model is also more sensitive to the Reynolds number reduction, as can be concluded by comparing Figs. 16 and 17. The former shows $C_L$ vs $\alpha$ at moderate and low Reynolds numbers for the baseline model, and the latter shows these results for the S1.5-LL model. The lift coefficient of the baseline model is reduced, mainly in the range $0 \leq \alpha \leq 5$ deg, analogous to the observations made at the lower aspect ratio. Now, this is easily understood by analyzing and comparing Figs. 18 and 19, which illustrate the behavior of the boundary layer at $\alpha = 3$ deg, for moderate and low Reynolds numbers, respectively. The immediate conclusion is that, in both cases, the boundary layer separates in the aft section of the wing. However, at moderate Reynolds numbers, it reattaches to the surface forming a recirculation bubble, while at low Reynolds numbers, the separated shear layer can no longer reattach to the wing surface. Flow visualization of the S1.5-LL model still showed the formation of a

![Fig. 14](image1.png)  \textit{Fig. 14} $C_L$ vs $\alpha$ for the B1 wing model at $Re = 70,000$ and 140,000.

![Fig. 15](image2.png)  \textit{Fig. 15} $C_L$ vs $\alpha$ for the S1-LL wing model at $Re = 70,000$ and 140,000.

![Fig. 16](image3.png)  \textit{Fig. 16} $C_L$ vs $\alpha$ for the B1.5 wing model at $Re = 70,000$ and 140,000.

![Fig. 17](image4.png)  \textit{Fig. 17} $C_L$ vs $\alpha$ for the S1.5-LL wing model at $Re = 70,000$ and 140,000.

![Fig. 18](image5.png)  \textit{Fig. 18} Flow visualization for the B1.5 wing model at $Re = 140,000$ and $\alpha = 3$ deg. Note the approximate locations of the separation and reattachment points denoted by “S” and “R”, respectively, and the wing section contour at the visualization plane.

![Fig. 19](image6.png)  \textit{Fig. 19} Flow visualization for the B1.5 wing model at $Re = 70,000$ and $\alpha = 3$ deg. Note the approximate location of the separation point denoted by “S” and the wing section contour at the visualization plane.
(very) small separation bubble, but its size was negligible if compared with those previously mentioned, and thus difficult to document photographically (not shown). Hence, these observations provide a rational explanation for the lower sensitivity of these models to the Reynolds number variation. Another interesting note is that the sinusoidal model characterized by milder deviations with respect to the baseline model (S1.5-SL model) is more affected by the Reynolds number reduction at low angles of attack (cf., Fig. 10). This is also seen for the lower aspect ratio (cf., Fig. 9) but to a lesser extent. The effective benefits of using a sinusoidal leading edge with large amplitude and wavelength can be appreciated in Fig. 20, where the normalized lift coefficient is plotted as a function of angle of attack at low and moderate Reynolds numbers for α ≥ 10 deg. Again, we must not overlook the large benefits also obtained at low angles of attack. However, for α ≥ 10 deg, maximum Cl improvements of 45% over the baseline model can be obtained with an average penalization of approximately 5% in the range 10 ≤ α ≤ 16 deg. The maximum overall penalization occurring at α = 16º for the sinusoidal model (on the order of 10%) is just about half the maximum penalization at the higher Reynolds number. In addition, the drag polar in Fig. 21, where the performance of baseline and sinusoidal models is again compared for the two investigated Reynolds numbers, demonstrates that higher Cdp values are only obtained for the wing with a modified leading edge in a very limited range before baseline stall. Even so, the increment in drag due to the modification is marginal at the lower Reynolds number and, for this regime, higher Cdp values actually result at low incidence.

IV. Conclusions

The aerodynamic characteristics of wings with LARs, rectangular planforms, and sinusoidal leading edges were studied through a series of wind-tunnel tests and compared with the results of a baseline model. Of primary interest were the effects of aspect ratio, leading-edge geometry, and Reynolds numbers on the lift forces. The amplitude of the leading-edge protuberances used in the models was 6 and 12% of the mean chord length, and the wavelengths were 25 and 50% of the mean chord length.

At a Reynolds number of Re = 140,000, the protuberances caused a reduction in lift coefficient for angles of attack below the baseline model stall angle. For α ≥ 0, the results depend strongly on the aspect ratio. For wings with an aspect ratio of 1.5, the sinusoidal models presented a much smoother stall than the baseline model and it was possible to achieve maximum lift coefficient gains of the order of 45%. Moreover, the use of a sinusoidal leading edge eliminated the aerodynamic hysteresis associated with the abrupt and severe baseline model stall. In turn, the baseline model with an aspect ratio of 1, by action of the wingtip vortices (more influential for lower AR) experienced only a minor loss of lift at the stall point. This was followed by a continuous increase in lift up to the maximum angle of attack. Hence, the gains introduced by the protuberances do not clearly prevail over the losses at the higher Reynolds number.

The reduction of the Reynolds number to Re = 70,000 produced drastically different results in the wings with and without protuberances. If, on one hand, the wings with protuberances were fairly insensitive to the variation of the Reynolds number, on the other hand, the capability of baseline models to generate lift deteriorated considerably. This led to an overall increase of the beneficial effects of the sinusoidal models, especially at low angles of attack. Hence, one can say that sinusoidal leading-edge lifting surfaces are clearly less prone to performance deterioration. This is the most important result of the present study, and drag polar data reinforced this view.

Furthermore, our experiments also indicated that both the amplitude and wavelength of protuberances play important roles in the resulting aerodynamic forces produced by these LAR wings.

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