

An experimental study on a Natural Laminar Flow airfoil at off-design conditions

H. D. Lim^{1,*}, N.A. Siddiqui¹, Y.D. Cui¹, Y.W. Chin¹, Q.V. Nguyen¹, B.Y.J. Wong¹, C.M.J. Tay¹

1: Temasek Laboratories, National University of Singapore, Singapore 117411, Singapore

*Corresponding author: d.h.lim@nus.edu.sg

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ABSTRACT

This study presents an experimental investigation on a natural laminar flow airfoil under operating conditions that deviate significantly from its design point. Aerodynamic force measurements revealed the section drag, lift and pitch moment coefficients converge for Reynolds number $Re \geq 462k$. At lower Reynolds numbers ($Re \leq 308k$), substantially reduced aerodynamic efficiencies and irregular variations of the aerodynamic forces with angle of attack were observed, which are attributed to flow separation without reattachment based on the particle image velocimetry (PIV) measurements. A discrepancy between the PIV and oil film interferometry (OFI) surface flow visualisation was observed on the suction side of the airfoil at $Re=500k$ and $\alpha = 0^\circ$, where the PIV results indicate fully attached flow, while the OFI results reveal laminar boundary layer separation and turbulent reattachment. This discrepancy is attributed to the loss of PIV data in the near-wall region, coupled with the small vertical extent of the separation bubble, which can be on the order of 1% of the chord length.

1. Introduction

Natural laminar flow (NLF) airfoils reduce cruise drag by shifting the maximum thickness aft, thereby delaying the transition of the boundary layer from laminar to turbulent (Selig et al., 1995). However, laminar boundary layers are highly sensitive to adverse pressure gradients and can separate prematurely, leading to a significant loss of lift and an increase in drag. Consequently, NLF airfoils often perform poorly under off-design conditions, yielding a relatively narrow range of optimal operating conditions. In addition, the onset of stall and flow separation in NLF airfoils can occur abruptly, including during critical phases such as take-off and landing, which can compromise flight safety. It is therefore essential to thoroughly understand the aerodynamics of a NLF airfoil, including at low Reynolds number and off-design conditions, before practical implementation.

At low Reynolds number, flow separation physics dominate. The flow separation physics of a traditional airfoil at Reynolds number of below $Re < 10^6$ has been extensively studied and can serve

as a useful reference to guide our understanding on the NLF airfoil (Winslow et al., 2018). At low Reynolds number ($10,000 < Re < 50,000$), the laminar boundary layer undergoes flow separation close to the trailing edge of the airfoil, with the separation point moving towards the leading edge with increasing angle of attack. Reattachment does not occur. As the Reynolds number increases ($50,000 < Re < 100,000$), the separation point shifts forward towards the leading edge. The separated turbulent shear layer entrains momentum from the free-stream and reattaches to the airfoil, creating a large laminar separation bubble in the process. With increasing angle of attack, the reattachment point shifts towards the trailing edge, resulting in relatively large laminar separation bubbles that can be 15-40% of the chord. At high Reynolds number ($Re > 500,000$), the laminar boundary layer experiences strong adverse pressure gradient close to the leading edge, separates early but quickly reattaches to the airfoil, thus creating a small laminar separation bubble in the process. The turbulent boundary layer can then either remain attached (i.e., low angle of attack) or separate again close to the trailing edge (i.e., high angle of attack).

One of the key phenomena associated with flow separation is the behaviour of the laminar separation bubble, which remains an active area of research. Hu & Yang (2008) observed a stretched laminar separation bubble on a low Reynolds number airfoil, with the height of the bubble measured at around 1% chord length and length of the bubble at around 20% chord length. Wang et al. (2014) observed that the freestream turbulence intensity has a more pronounced effect on the behaviour of the separation bubble at lower Reynolds number, and that there are several similarities between increasing turbulence intensity to that of increasing Reynolds number. Koning et al. (2023) defined bubble flapping as a laminar separation bubble that do not feature steady reattachment. However, large-scale spanwise flow structures shed and interact with the turbulent boundary layer, resulting in reattachment only in the time-averaged sense. For their Eppler 387 airfoil, they observed bubble dominated flow physics at $Re \leq 460k$.

Despite the extensive body of literature on airfoil flow separation, aerodynamic testing at low Reynolds numbers remains particularly challenging. In this regime, the flow is often strongly three-dimensional, and airfoil performance is highly sensitive to Reynolds number and boundary conditions (Winslow et al., 2018). In addition, the choice of drag measurement technique—such as wake deficit methods versus force balance measurements—can introduce significant discrepancies in the reported results (Selig et al., 1996). Consequently, it is essential for experimentalists to be well versed in multiple aerodynamic measurement approaches and to reconcile their findings into a coherent physical interpretation. Moreover, most studies on NLF airfoils have traditionally focused on moderate to high Reynolds numbers regimes, including transonic conditions, where the laminar boundary layer is more robust and the potential for drag reduction is greater (Fujino et al., 2003). As a result, NLF airfoils operating at low Reynolds numbers remain under-represented in the literature.

In this study, we investigate a NLF airfoil which was originally designed for a Reynolds number

of 2 million using an in-house optimisation framework (Li et al., 2022), but is experimentally investigated under operating conditions that deviate significantly from its design point. A range of complementary measurement techniques is employed, including an external force balance for aerodynamic loads, particle image velocimetry (PIV) for detailed flow-field characterization, and oil film interferometry (OFI) for surface flow visualization. The results from these methods are synthesized to develop a coherent physical interpretation of the flow separation phenomena. We anticipate that the combined experimental approach and the resulting insights into low-Reynolds-number NLF airfoil separation physics will be of interest to attendees of the Lisbon Laser Symposium.

2. Experimental Setup

The experiments were performed in the closed-loop wind tunnel facility in the National University of Singapore as shown in Fig. 1(a). The test section has a cross-sectional area of $0.6 \text{ m} \times 0.6 \text{ m}$ and a length of 2 m. The free-stream velocity ranges between $U_\infty = 1.5 \text{ m s}^{-1}$ to 90 m s^{-1} , and the associated turbulence intensities are below 0.15% for the velocity range $15 \text{ m s}^{-1} < U_\infty < 70 \text{ m s}^{-1}$ and below 0.25% for $U_\infty > 70 \text{ m s}^{-1}$.

The NLF airfoil was designed for Reynolds number of $\text{Re} = 2 \times 10^6$ using an in-house optimisation code (Li et al., 2022). Two versions of the NLF airfoil were fabricated and anodised to support different experimental objectives: one with a chord length of $c = 120 \text{ mm}$ and another with $c = 240 \text{ mm}$. The smaller airfoil was used for lift and drag measurements to avoid overloading the force balance and limit the maximum blockage ratio to a conservative estimate of $\leq 10.2\%$ at $\alpha = 20^\circ$. The larger airfoil enabled testing at higher Reynolds numbers, albeit over a limited range of angles of attack with the maximum blockage ratio limited to $\leq 10.7\%$ at $\alpha = 5^\circ$, and provided improved spatial resolution for mid-span flow-field measurements. Unless otherwise stated, all results presented in this study are based on experiments conducted with the smaller NLF airfoil; oil film interferometry surface flow visualisation was performed exclusively on the larger airfoil.

A 3-component external balance was used to measure the lift and drag forces of the NLF airfoil and to control the angle of attack up to pitch angle accuracy of $\pm 0.1^\circ$. The lift and drag coefficients were computed based on 3000 time-averaged data points acquired at 500 Hz sampling frequency. Systematic and careful testing (i.e., optimisation of mounting plate, gap size, biannual instrumentation calibration, etc) was performed to ensure highly repeatable results. Oil film interferometry was used to visualise the flow close to the flow separation and reattachment locations. Kapton tape ($50 \text{ }\mu\text{m}$ thick) was applied to the airfoil to improve reflectivity, and a monochromatic LED was used to illuminate the oil and reveal the interference fringe patterns. Silicon oil with kinematic viscosities ranging between 5 to 50 cSt was introduced using a pipette. A DSLR camera was used to record the oil film photographs when the oil flow has stabilised.

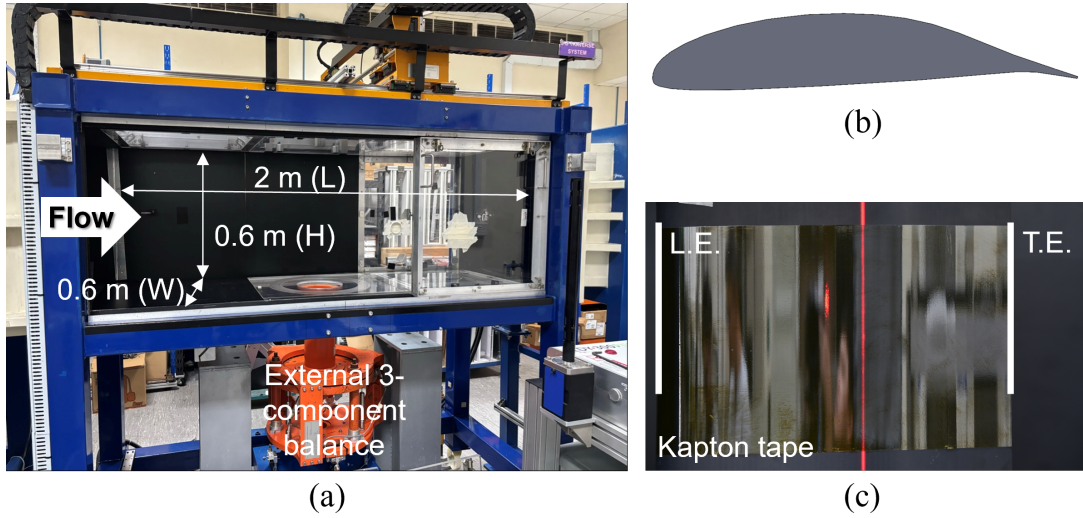


Figure 1. (a) Wind tunnel test section, (b) NLF airfoil (not to scale) and (c) Kapton tape applied onto the suction surface of the NLF airfoil.

High-speed PIV was performed to measure the 2D velocity field on the suction side of the airfoil and in the wake region. A dual cavity, 30 mJ/pulse, Litron Nd:YLF laser was used to produce a 1 mm thick laser sheet to illuminate SAFEX seeding particles which has a nominal diameter of $1\ \mu\text{m}$. A Phantom Miro 320S with 1920×1200 image resolution was used to capture the particle images, with the seeding density and particle displacement optimised (e.g., one-quarter rule) based on the study by Keane & Adrian (1991). Consequently, all particle images were post-processed using the LaVision DaVis 10 software. Geometric masking was performed in regions where there is intense laser reflection or had a lack of optical access. For the most severe laser reflection cases, around 1 mm of the data from the airfoil surface was not usable and had to be masked. The images were pre-processed using a time filter which subtracted the minimum intensity values at each pixel to reduce background noise. Multi-grid multi-pass cross-correlation was performed, with a final interrogation window size of 16×16 , 75% overlap ratio, and spurious vectors rejected based on a peak ratio $Q < 1.2$ rejection criteria and the universal outlier detection (DaVis' adaption of the original median test) filter. The correlation values map averaged between 0.8 to 0.9 for all test cases. A 5×5 median filter was used to replace spurious vectors that were removed. The final vector resolution is $R_{PIV} = 0.37\ \text{mm}$.

3. Results and Discussions

The aerodynamic properties shown in Fig. 2 indicate that the section drag, lift and pitch moment coefficients of the NLF airfoil converge for Reynolds number $\text{Re} \geq 462\text{k}$. The pitch moment is relatively linear for $\alpha \leq 8^\circ$, which is a desirable aerodynamic property as it reduces the probability of sudden pitch up during near stall conditions. At lower Reynolds number ($\text{Re} \leq 308\text{k}$), C_d in-

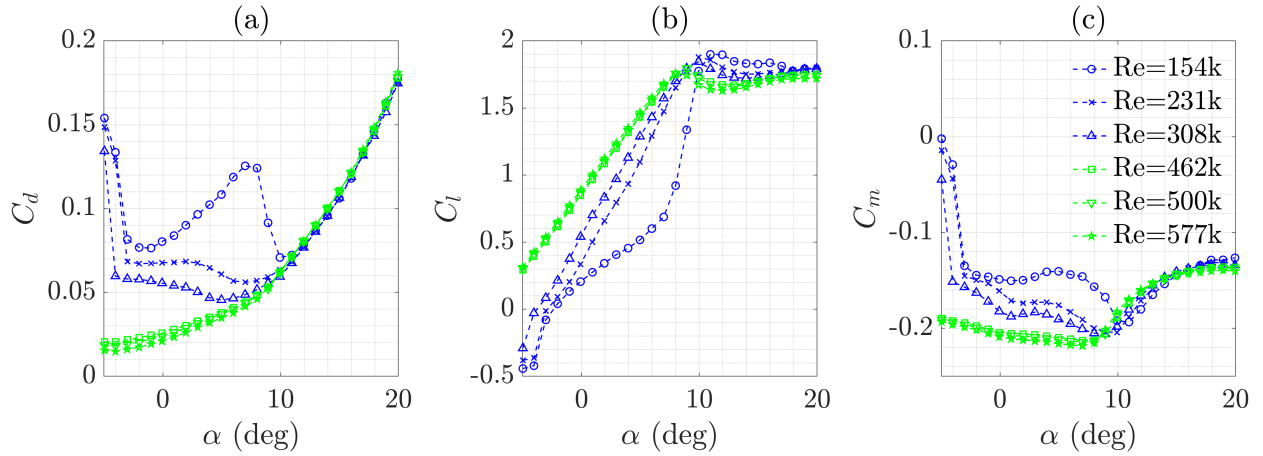


Figure 2. Aerodynamic properties of the NLF airfoil at various Reynolds number – (a) section drag , (b) section lift and (c) section pitching moment curves.

creases while C_l decreases markedly, particularly for $\alpha \leq 8^\circ$, resulting in much lower aerodynamic efficiencies. A pronounced C_d peak can also be observed at $Re=154k$, which is comparable to one of the C_d results reported for the Eppler 387 airfoil at $Re=60k$ by Koning et al. (2023).

Notably, Koning et al. (2023) observed two distinct groups of aerodynamic force results: one characterised by high section drag (i.e., increasing C_d without a sharp peak), and another which has low section drag (i.e., pronounced C_d peak similar to our $Re=154k$ results). They attributed this to a ‘dual flow state’ where both laminar separation and turbulence reattachment are occurring. At $Re=60k$, they postulated that their airfoil was on the verge of stalling and barely reattaching in most conditions, hence the momentary unsteady reattachment makes the aerodynamic measurements particularly sensitive to boundary conditions. In contrast, we did not observe any dual flow states in the present study. Repeated experiments at $Re=154k$ yielded highly consistent and repeatable aerodynamic measurements.

To reveal deeper insights into the flow field, the mean velocity vectors and velocity deficit contour maps for selected test cases from the PIV measurements are plotted in Fig. 3. Based on the mean velocity vectors, reversed flow can be observed for the $Re=230k$ and $\alpha = 0^\circ$ test case (Fig. 3(a)) starting from around $x/c = 0.7$. The presence of a separation bubble without reattachment (Fig. 3(a)) was categorised by Wang et al. (2014) as a low Reynolds number regime B, which can be described as a laminar boundary layer that separates near the trailing edge. This flow separation behaviour explains the higher drag and lower lift aerodynamic properties previously presented in Fig. 2.

Flow separation and separation bubble was not observed for the other two $Re=500k$ test cases, and the velocity deficit in the wake region is much smaller than compared to the $Re=230k$ and $\alpha = 0^\circ$ test case. This result is consistent with the improved aerodynamic efficiency data previously observed in Fig. 2. However, the flow field observed here would be categorised by Wang

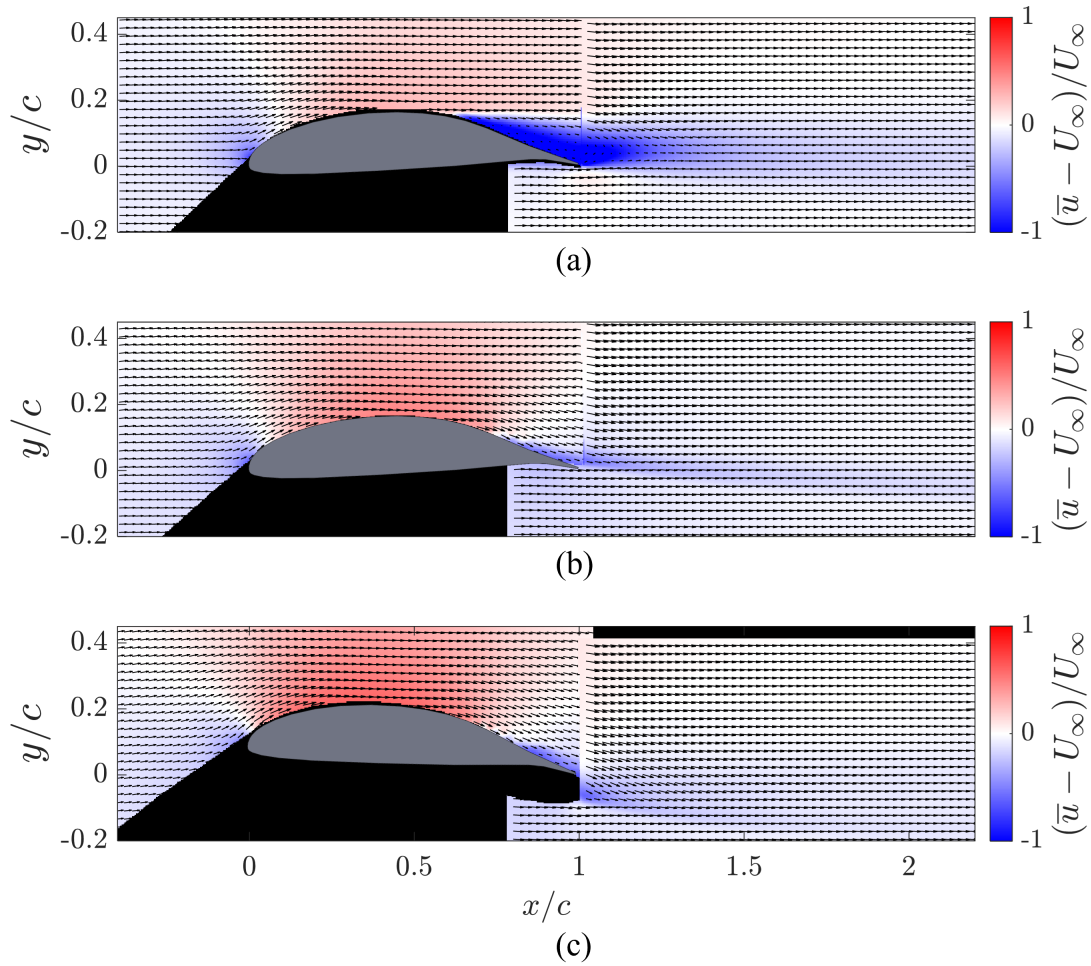


Figure 3. Mean velocity vector (plotted at reduced resolutions) and velocity deficit contours for the NLF airfoil at (a) $Re=230k$ and $\alpha=0^\circ$, (b) $Re=500k$ and $\alpha=0^\circ$, and (c) $Re=500k$ and $\alpha=5^\circ$.

et al. (2014) as a high Reynolds number regime F (i.e., fully attached turbulent boundary layer), which is counter-intuitive for us as we should have observed flow fields associated with the moderate Reynolds number regime E (i.e., laminar separation followed by turbulent reattachment) first. Furthermore, our OFI surface flow visualisation results as shown in Fig. 4 suggests that there should be laminar boundary layer separation at $x/c = 0.62$ and turbulent reattachment (in the time-averaged sense) at $x/c = 0.71$. Based on these results, the most likely conclusion is that there is a very thin separation bubble close to the suction side of the airfoil, in the order of 1 mm height, and that the PIV technique was not able to capture this due to the intense laser reflection close to the airfoil surface. This conclusion is consistent with the study by Hu & Yang (2008), who notably measured a stretched laminar separation bubble with height of only around 1% chord length.

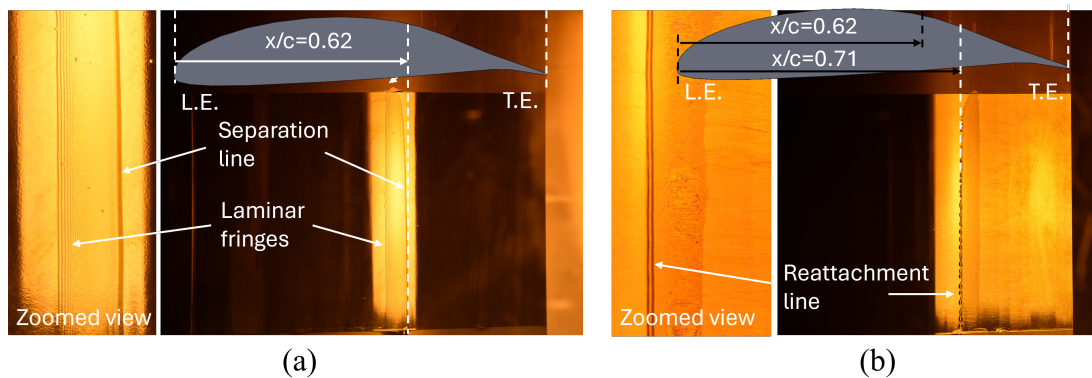


Figure 4. Oil film interferometry surface flow visualisation on the suction side of the NLF airfoil at $Re=500k$ and $\alpha=0^\circ$, showcasing the (a) flow separation line and (b) reattachment line.

4. Conclusions

In this study, the NLF airfoil was experimentally investigated under off-design conditions over a Reynolds number range of $154k \leq Re \leq 577k$, using a three-component external force balance, two-dimensional PIV, and OFI for surface flow visualization. The results show that the aerodynamic force coefficients converge for Reynolds numbers $Re \geq 462k$. In contrast, at lower Reynolds numbers ($Re \leq 308k$), substantially reduced aerodynamic efficiencies and irregular variations of the aerodynamic forces with angle of attack were observed. The PIV results indicate flow separation without reattachment for the NLF airfoil at $Re=230k$ and $\alpha = 0^\circ$ which corroborates well with the corresponding aerodynamic force measurements. In contrast, for the $Re=500k$ cases at both $\alpha = 0^\circ$ and $\alpha = 5^\circ$, the PIV results suggest fully attached flow. This observation is not consistent with the OFI results, which for the $Re=500k$ and $\alpha = 0^\circ$ test case, revealed a clearly identifiable flow separation line at $x/c=0.62$ and reattachment line at $x/c=0.71$ (in the time-averaged sense). This discrepancy is attributed to the loss of PIV data in the near-wall region, together with the small vertical extent of the separation bubble, which can be on the order of 1% of the chord length. To address this limitation, additional PIV experiments are planned using the larger NLF airfoil, in combination with commercially available ultra-black coatings and optimised laser optics to minimize near-wall laser reflections.

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