Effect of Freestream Turbulence on Laminar Separation Bubbles and Flow Transition on a Low Reynolds Number Airfoil

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science Graduate Department of the Institute for Aerospace Studies University of Toronto

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The effect of freestream turbulence intensity on the laminar separation bubble and flow transition over an SD7003 airfoil was investigated. Measurements were performed for Reynolds numbers ranging from 60,000 to 250,000, various angles of attack and turbulence intensities between 0.05% and 0.99%. Boundary layers with a separation bubble were found to develop a turbulent boundary layer more rapidly than those without. The trends in the skin friction downstream of the peak corresponding to the development of a turbulent boundary layer were very similar for all turbulence intensities, suggesting the turbulent boundary layer forming downstream of transition was not significantly affected by the turbulence intensities investigated. The fluctuating velocity spectra showed that the increase in freestream turbulence intensity introduced sufficient energy to the laminar boundary layer to initiate transition before the flow was able to separate at an angle of attack of 4° but not at 8°.
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Chapter 1

Introduction

A wide range of fields have turned to unmanned aerial vehicles (UAVs) in order to accomplish complex tasks that were either not possible before or were far more arduous without them. Compared to commercial aircraft, unmanned aerial vehicles are smaller, more lightweight, have better maneuverability, and do not require an onboard pilot. These advantages have made UAVs quite versatile in terms of their uses. Applications for UAVs are found in a number of industries, including crop management, surveying, and law enforcement. As technology develops, UAVs are becoming more advanced, which makes them more attractive to new and different industries and this poses unique challenges. The combination of these factors has fuelled significant amounts of research into UAVs and their aerodynamics over the past few decades.

Since UAVs are generally small and fly at low speed they often operate at low Reynolds numbers. This low Reynolds number regime leads to unique flight and flow conditions that make studying UAVs and low Reynolds number airfoils a challenging endeavour. Namely, the operation of UAVs at low Reynolds numbers makes them susceptible to laminar separation. This flow separation leads to the formation of a separated shear layer that may reattach, forming a laminar separation bubble (LSB). Within LSBs, a region of recirculating flow exists. These separation bubbles are very sensitive to flow conditions, which makes them quite difficult to study and compare across different experimental facilities. Not only is it difficult to study these low Reynolds number flows experimentally, but it is also quite difficult to model them. In order to design and optimize low Reynolds number airfoils better numerical models are needed. Despite significant amounts of research over the past decades [3, 8, 9, 10, 17, 27, 32, 33], the fluid mechanics associated with low Reynolds number airfoils is still not fully understood.

This thesis aims to establish an account of the effects that freestream turbulence intensity has on the laminar separation bubble and the flow transition over an SD7003
airfoil. The focus will be on low freestream turbulence intensities (0-1%). The following sections of the thesis will include a review of the relevant literature and studies performed on low Reynolds number airfoils and laminar separation bubbles, a detailed description of the experimental methodology, the results from the current study, and conclusions and recommendations for future work.

1.1 Low Reynolds Number Airfoils

The most important aspect of any surface capable of generating lift is its profile. A wide variety of airfoil designs exist and are used depending on the application and corresponding Reynolds number. The chord Reynolds number, \( Re_c \), is defined as,

\[
Re_c = \frac{U_\infty c}{\nu},
\]

where \( U_\infty \) is the freestream velocity, \( c \) is the chord of the airfoil, and \( \nu \) is the kinematic viscosity of the fluid. The low Reynolds number regime is defined as being anywhere between 15,000 and 500,000 [28]. Airfoils operating in this range have to deal with unique flow phenomena, such as laminar flow separation. The flow over a low Reynolds number airfoil separates because of the adverse pressure gradient, which occurs due to the surface curvature of an airfoil. Over the surface of an airfoil, regions of lower than freestream static pressure exist, typically on the suction side of the airfoil (upper surface). In these low pressure regions, the flow over the airfoil is accelerated. Pressure recovery over the airfoil occurs through the adverse pressure gradient. For airfoils that operate at larger Reynolds numbers (i.e., airfoils used for commercial aircraft), the flow over the airfoil transitions near the leading edge resulting in the formation of a turbulent boundary layer. Turbulent boundary layers have improved separation resistance compared to laminar boundary layers. For airfoils operating at low Reynolds numbers, however, the flow transitions further along the airfoil, which means the adverse pressure gradient is now acting on a laminar boundary layer. Laminar boundary layers are much more susceptible to flow separation making it more difficult for them to navigate the adverse pressure gradient. This defining characteristic of a low Reynolds number flow means that low Reynolds number airfoils are susceptible to laminar separation. This flow separation leads to a decrease in the aerodynamic performance of an airfoil.

If the flow separates, a separated shear layer is formed. Depending on the flow conditions (i.e., Reynolds number, angle of attack, turbulence intensity, etc.) the separated shear layer may undergo transition and reattach, forming a laminar separation bubble.
Chapter 1. Introduction

A laminar separation bubble is illustrated in Figure 1.1. In a time-averaged sense, a laminar separation bubble is a region of recirculating flow. Laminar separation bubbles have been found to have a critical impact on aerodynamic performance. The size of a laminar separation bubble is a major contributor to the overall effect a separation bubble has on the aerodynamic performance of an airfoil. In a study on the Wortmann FX63-137 airfoil, Bastedo Jr. and Mueller [3] found that at an angle of attack of 6° a short laminar separation bubble replaced the long bubble that formed at lower angles of attack. This resulted in a significant increase in lift and a slight reduction in drag. With further increases in angle of attack the laminar separation bubble decreased in length until it eventually burst, resulting in a dramatic decrease in lift and an increase in drag [3]. Counsil and Boulama [10] compared the NACA 0012 and SD7003 airfoils. They concluded that the thickness of a laminar separation bubble and the location where it is situated on the airfoil are more important to aerodynamic performance than the length of the separation bubble, since the SD7003 airfoil was found to perform better than the NACA 0012 airfoil even though the SD7003 airfoil produced longer separation bubbles over its surface.

Figure 1.1: Illustration of a laminar separation bubble from Håggmark et al. [16]

1.2 Laminar Separation Bubbles

1.2.1 Laminar Separation Bubble Classification

Laminar separation bubbles can be classified into two categories, short bubbles and long bubbles. Long bubbles are found to cover 20–30% of the airfoil chord, while short bubbles
are found to cover only a few percent of the airfoil chord [24]. The size of a laminar separation bubble is very sensitive to the flow conditions. As the angle of attack of an airfoil increases, the adverse pressure gradient becomes stronger leading to the bursting of a short laminar separation bubble and the formation of a long separation bubble. Gaster [15] stated that the pressure distribution that resulted from an unseparated flow determined the shape of the bubble for a similar flow containing a laminar separation bubble. This conclusion led Gaster [15] to propose a two-parameter bursting criterion composed of the Reynolds number based on the momentum thickness at separation, $Re_{\theta_s}$, and the term $(\theta_s^2/\nu)(\Delta U/\Delta x)$, where $\Delta U$ is the velocity increase over the bubble length $\Delta x$. Gaster [15] also determined that low frequency oscillations in the mean flow were a characteristic of a long bubble and a long bubble was also very sensitive to acoustically excited disturbances. In a numerical study on a flat plate, Pauley et al. [35] further suggested that short bubbles display vortex shedding while long bubbles do not, which was in contrast to the findings of Watmuff [45], where a short bubble displayed no signs of vortex shedding.

Some researchers have suggested that the bursting of a bubble may be associated with a change from a convective instability to that of an absolute instability [1]. Diwan et al. [11] questioned this since a long bubble involves a more gradual reattachment, which is inconsistent with an absolute instability. They then proposed a bursting criterion that not only took into account the length of the bubble but the maximum height as well, since transition within a separation bubble occurs around the streamwise location where the maximum height of the bubble is located. They proposed the non-dimensional pressure gradient parameter $P = \frac{\nu^2}{\Delta x}$, where $\frac{\Delta U}{\Delta x}$ is the change in velocity over the bubble length. By plotting their non-dimensional pressure gradient parameter against the Reynolds number based on the velocity at the streamwise location where the maximum bubble height occurred, they were able to see a clear grouping of short bubbles and long bubbles for data taken from experiments involving a flat plate.

1.2.2 Transition

Laminar separation bubbles form when the unstable separated shear layer undergoes transition just downstream of the point of separation and the flow reattaches. Within a boundary layer the transition from laminar to turbulent flow occurs due to an incipient instability. Initial disturbances are introduced into the boundary layer and begin to grow. This early growth is described by linear stability theory. As these disturbances grow, three-dimensional and nonlinear interactions begin to take place in the form of secondary
instabilities [20]. At this stage in the transition process the growth of disturbances is rapid and the eventual breakdown to turbulence occurs quickly.

In the case of a laminar separation bubble, where the flow separates from the wall, a different transition process occurs in the separated shear layer. Upstream of separation and in the early portion of the bubble however, the transition process can still be described by linear stability theory [21, 37, 46]. The presence of Tollmien-Schlichting waves in the laminar boundary layer ahead of separation and in the separated shear layer just past separation has been documented to support this [2, 22]. Further downstream of separation, Kelvin-Helmholtz instabilities dominate the transition process within the separation bubble. These Kelvin-Helmholtz instabilities develop due to the separated inflectional velocity profile [23]. This change from Tollmien-Schlichting waves to Kelvin-Helmholtz instabilities has been shown to occur smoothly [37]. Driven by the Kelvin-Helmholtz instabilities, the shear layer rolls up into vortices that drive the reattachment of the separated shear layer through entrainment of higher-momentum fluid [23]. This portion of the transition process exhibits signs of exponential growth and nonlinear interactions [46].

Burgmann et al. [8] investigated the structure of the vortices at the downstream end of a separation bubble in order to gain further insight into the Kelvin-Helmholtz instabilities. They identified and attributed a significant rise in the maximum power spectral density, $PSD_{\text{max}}$, of the wall-normal velocity to the onset of vortex roll-up in the separated shear layer, since these $PSD_{\text{max}}$ values were associated with frequencies between 0 and 5 Hz. These findings further reinforced the fact that transition within the separation bubble is dominated by Kelvin-Helmholtz instabilities.

As discussed, evidence of vortex shedding from separation bubbles has been well documented [17, 23, 35]. As a result of this vortex shedding, bubbles have been found to flap in the streamwise direction [9]. This process is illustrated in Figure 1.2. A flapping in the wall-normal direction also occurs due to the roll-up process in the separated shear layer. As vortices form in the shear layer, they begin to travel downstream causing the bubble to flap in the wall-normal direction.

Examining the spectra of disturbances within a separation bubble it is evident that frequency bands of oscillations are present, as illustrated in Figure 1.3 [12]. After the point of separation a band of unstable Fourier components (termed a wave-packet) becomes visible in the spectra centred around a fundamental frequency [46]. As the wave-packet travels downstream the amplitude of disturbances grows until the eventual breakdown to turbulence. Frequency bands of oscillations centred at a frequency lower than that of the fundamental frequency have been attributed to bubble flapping [12, 14]. Other
low frequency bands occurring at a subharmonic frequency of the fundamental frequency have been associated with the merging of roll-up vortices [47].

Figure 1.2: Illustration of the mean and instantaneous flow field over an airfoil highlighting bubble flapping from Burgmann and Schröder [9].

Figure 1.3: Spectra of disturbances within a laminar separation bubble from Dovgal et al. [12].

1.2.3 Laminar Separation Bubble Characterization

Laminar separation bubbles are most commonly characterized using three parameters, the separation point, transition point, and reattachment point. These parameters can
be determined using a number of different techniques, including pressure distributions, hot-wire measurements, PIV measurements and oil flow measurements. An example of laminar separation bubble characterization using surface pressure measurements is shown in Figure 1.4. The point on the pressure distribution that signifies the start of a pressure plateau indicates the point of separation. The transition point is located where the pressure plateau ends and the reattachment point corresponds to the location where the separated pressure distribution would cross the unseparated turbulent pressure distribution that would form on the airfoil at the same angle of attack [2]. An issue with the use of pressure distributions to characterize the separation bubble is surface pressure tap resolution. On an airfoil surface there are a finite number of pressure taps, so how well the pressure measurements resolve the bubble is dependent on how many pressure taps are included and the spacing between those taps. It is also quite difficult to identify the point of separation from a pressure distribution because in some instances it is hard to clearly identify where a pressure plateau begins.

Figure 1.4: Pressure distributions for an SD7003 airfoil from Sutton [40]. The solid line distribution contains a separation bubble. The dashed line distribution does not contain a separation bubble. The points of separation, transition, and reattachment are identified with S, T, and R respectively.

Alternatively, hot-wire measurements can be used not only to determine the points of separation, transition and reattachment, but also bubble thickness. Hot-wire measurements are also useful to trace disturbance growth throughout the separated shear layer,
which in turn can be used to identify the final breakdown to turbulence. In addition, bubble flapping can be identified. However, since hot-wire measurements do not indicate the direction of the flow there are errors with the measurements due to the reverse flow in the separation bubble.

Another velocity measurement technique that can be used to characterize the laminar separation bubble is particle image velocimetry (PIV). With the use of PIV measurements a sense of the flow field around the airfoil can be gained. However, the spatial resolution of the setup can lead to errors in the near-wall velocities at the leading edge of the airfoil, since the boundary layer and separated shear layer in this area are quite thin and large interrogation windows cannot resolve the large velocity gradients [32].

Oil flow measurements are another alternative to characterize the laminar separation bubble. With the use of one such technique, oil film interferometry, the locations of separation and reattachment can be determined from the changes in flow direction of the oil. Unfortunately, difficulties in characterizing the laminar separation bubble arise when the airfoil surface is not ideal for fringe-imaging techniques. In this case, it can be difficult to clearly locate the separation point.

1.2.4 Effects of Flow Conditions

Flow conditions have significant effects on laminar separation bubbles. With an increase in the angle of attack, the separation bubble has been found to move towards the leading edge of the airfoil and decrease in length [8, 17, 34]. Not only does the bubble become shorter but it also decreases in thickness. As stated earlier, however, at a certain angle of attack the short laminar separation bubble will burst leading to the development of a long laminar separation bubble or potentially the airfoil will stall. Burgmann et al. [8] found that with an increase in the angle of attack the frequency of vortex formation increased. At higher angles of attack, the local velocity around the shear layer is larger and the laminar separation bubble is thinner. This creates a larger wall-normal velocity gradient that causes the separated shear layer to roll-up in shorter intervals [8]. In addition, Boutilier and Yarusevych [6] noted an increase in the maximum disturbance growth rate with angle of attack. This in turn results in disturbance amplitudes that can trigger transition in the separated shear layer, leading to shorter bubbles at higher angles of attack.

As the Reynolds number is increased, the bubble thickness decreases and the bubble moves upstream [34, 10]. Though both the Reynolds number and angle of attack have similar effects on the separation bubble, there are differences. In a study comparing two
airfoils, Counsil and Boulama [10] found that while increasing either the angle of attack or the Reynolds number caused the laminar separation bubble to move upstream, the angle of attack had a more pronounced effect on the separation bubble characteristics. The effects of angle of attack and Reynolds number on the laminar separation bubble characteristics are highlighted in Figure 1.5. The central frequency of disturbance amplification has also been found to increase with an increase in either the Reynolds number or the angle of attack [5].

![Figure 1.5: Separation (solid lines) and reattachment (dashed lines) locations for various angles of attack and Reynolds numbers from Boutilier and Yarusevych [5].](image)

Burgmann and Schröder [9] demonstrated that turbulence intensity significantly affects the mean flow field. They found that an increase in turbulence intensity from 1% to 1.5% led to a separation delay and resulted in an overall thinner bubble. They attributed these effects to an earlier transition. At the higher turbulence intensity transition is promoted, leading to an earlier onset of Kelvin-Helmholtz vortices thus resulting in a thinner bubble and smaller vortices. Through further analysis they concluded that turbulence intensity had little effect on vortex formation frequencies in the separation bubble, leading to the assumption that the size of the vortices, not the vortex roll-up process, is affected by the earlier transition brought on by the increase in turbulence intensity. Further investigation is required to support this assumption. An increase in freestream turbulence intensity has also been found to improve aerodynamic performance of an airfoil [44].
Issues Studying Laminar Separation Bubbles

Due to the sensitivities of the laminar separation bubble to flow conditions, investigating laminar separation bubbles can be quite difficult, especially when trying to compare sets of data from various studies. Across different test facilities the flow conditions can vary, for example the freestream turbulence intensity, and as discussed these changes can have significant effects on the laminar separation bubble. Ol et al. [32] studied the laminar separation bubble that formed on an SD7003 airfoil in three different facilities, a water tow tank, a wind tunnel, and a water tunnel. The separation point was measured to be between 0.18 – 0.33x/c across the three facilities and the reattachment point was measured to be between 0.58 – 0.63x/c. Of the three facilities, there was much better agreement between the water tow tank and the wind tunnel. Across the three facilities, the freestream turbulence intensities were all quite low (around 0.1%). Ol et al. [32] suggested that the discrepancies in the measured locations may be due to slight variations in the angle of attack or freestream turbulence intensity. This seems to indicate that small changes in freestream turbulence intensity, at low turbulence intensities, has quite a significant effect on the laminar separation bubble.

Olson et al. [33] highlighted some of the issues involved with characterizing the laminar separation bubble. The issues they drew attention to were separation and reattachment location dependence on the angle of attack at low angles of attack, the thinness of the laminar separation bubble around separation, and the sensitivity of the separation bubble to Reynolds number and freestream turbulence intensity. They noted that an increase in the freestream turbulence intensity promoted transition and hypothesized that at larger freestream turbulence intensities a bypass transition process influences the boundary layer state, resulting in a delay of separation.

1.3 Motivation

The work presented here was motivated by the lack of definitive conclusions surrounding the effects of freestream turbulence intensity on the transition process. Recently, as summarized above, hypotheses have been formed alluding to whether or not a change in freestream turbulence intensity only affects the location where transition occurs, and by result the size of the vortices involved in the shear layer roll-up process, or if a different transition process occurs entirely [9, 33]. Understanding the full effects of freestream turbulence intensity on the laminar separation bubble and the transition process is critical. As evidenced by Ol et al. [32] and Olson et al. [33], a change in freestream turbulence intensity...
intensity can have significant effects on the separation bubble, which brings into question the validity of comparing results across different facilities. As well, UAVs operate in a variety of different flow conditions and thus understanding the full extent of freestream turbulence intensity effects on the separation bubble and the transition process is important to optimizing the design of low Reynolds number airfoils.

1.4 Thesis Objectives

The objectives of this work are as outlined:

1. Investigate the effects freestream turbulence intensity has on the separation bubble. In particular, identify how sensitive the separation bubble is to small changes in freestream turbulence intensity at low turbulence intensities.

2. Determine the effect changes in turbulence intensity has on the skin friction on the SD7003 airfoil. Namely, how the negative and positive peak in skin friction are affected by turbulence intensity, how turbulence intensity affects the distance between those peaks and how sensitive the turbulent boundary layer that forms downstream of reattachment is to increases in turbulence intensity.

3. With the use of hot-wire measurements, investigate the effect freestream turbulence intensity has on the transition process of the flow over an SD7003 airfoil.
Chapter 2

Experimental Details

2.1 Wind Tunnel Facility

All experiments were performed in the low speed, low background turbulence wind tunnel at the University of Toronto Institute for Aerospace Studies. An illustration of the recirculating wind tunnel is shown in Figure 2.1. The test section in the wind tunnel is 5 m long, 1.2 m wide and 0.8 m high. The tunnel is capable of operating at a maximum freestream velocity of approximately 40 m/s. The freestream turbulence intensity at this velocity is 0.08%.

Figure 2.1: Illustration of the low speed wind tunnel at the University of Toronto Institute for Aerospace Studies from Hearst [18].
Four turbulence-generating grids were installed in the tunnel grid holder, located just upstream of the test section, in order to increase the freestream turbulence intensity within the tunnel for the desired test cases. A photograph of each grid is shown in Figure 2.2. W17, W18 and W42 were wire-mesh grids, while Rd38 was an aluminum round rod grid. The specifications of the grids are summarized in Table 2.1, where $d$ is the diameter of the grid bars, $M$ is the mesh length of the grid, $\sigma \equiv d/M(2−d/M)$ is the grid solidity, $T_u \equiv \langle u^2 \rangle^{1/2}/U$ is the freestream turbulence intensity at the leading edge of the airfoil ($U$ is the mean flow velocity and $u$ is the fluctuating velocity component), $\lambda$ is the Taylor microscale, and $L$ is the integral length scale. The leading edge of the airfoil was located at $X = 2.95$ m downstream of the tunnel grid holder and the turbulence intensity was determined using a hot-wire probe. Hot-wire measurements were performed using a single-wire probe with a 5 µm copper plated tungsten wire. The probe was operated with a Newcastle constant temperature anemometer and an overheat ratio of 1.6 [26]. A National Instruments BNC-2110 was used for data acquisition. Data was sampled at 20,000 Hz for 120 seconds and low-pass filtered at 9,200 Hz. Power spectral density plots of velocity for each grid at a $Re_c = 150,000$ are presented in Figure 2.3. The power spectral density plots at the three other Reynolds numbers are not presented here due to them being very similar. Since $X/M > 10$ for each grid, the turbulence produced by each grid was considered homogeneous [38]. Throughout the rest of the thesis the freestream turbulence intensities at $Re_c = 150,000$ will be used to refer to the different cases.

![Photographs of grids](image)

Figure 2.2: Photographs of an approximately 80 mm by 112 mm area of each of the turbulence-generating grids used to produce the turbulence intensities required for the experiments.
Table 2.1: Grid specifications and turbulence intensities produced at the leading edge of the airfoil. Turbulence intensities and length scales are presented for four Reynolds numbers 60,000, 100,000, 150,000, and 250,000.

<table>
<thead>
<tr>
<th>Grid</th>
<th>$d$ [mm]</th>
<th>$M$ [mm]</th>
<th>$\sigma$</th>
<th>$T_u$ [%]</th>
<th>$\lambda$ [mm]</th>
<th>$L$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>N/A</td>
<td>N/A</td>
<td>0.05</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
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<td>6.35</td>
<td>0.18</td>
<td>[0.11, 0.14, 0.17, 0.22]</td>
<td>[0.3, 0.8, 1.5, 3.1]</td>
<td>[15.8, 11.6, 10.4, 9.6]</td>
</tr>
<tr>
<td>W18</td>
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<td>12.7</td>
<td>0.18</td>
<td>[0.22, 0.30, 0.34, 0.38]</td>
<td>[0.4, 1.1, 2.0, 3.4]</td>
<td>[16.5, 12.7, 11.3, 10.3]</td>
</tr>
<tr>
<td>W42</td>
<td>3.0</td>
<td>12.7</td>
<td>0.42</td>
<td>[0.39, 0.55, 0.70, 0.78]</td>
<td>[0.8, 2.0, 3.7, 4.3]</td>
<td>[20.3, 18.0, 19.3, 18.2]</td>
</tr>
<tr>
<td>Rd38</td>
<td>6.8</td>
<td>32.0</td>
<td>0.38</td>
<td>[0.80, 0.90, 0.99, 1.06]</td>
<td>[1.5, 3.2, 4.5, 4.6]</td>
<td>[25.9, 22.9, 21.4, 20.0]</td>
</tr>
</tbody>
</table>

Figure 2.3: Power spectral density plots of velocity for each grid at the leading edge of the airfoil at $Re_c = 150,000$.

### 2.2 Model

All measurements were performed on an SD7003 airfoil model with a chord, $c$, of 254 mm and a span, $b$, of 754 mm. The model was manufactured using stereolithography (SLA) printing and was built out of Accura Bluestone material. Due to the build height restrictions of the SLA machine the model was designed as the combination of three sections held together by two aluminum spars. The two spars ran through the airfoil at chord locations of $x/c = 0.25$ and $x/c = 0.70$. The pressure taps were located on the middle section. A total of 39 surface pressure taps were laid diagonally along the upper and lower surfaces of the airfoil at midspan, in order to avoid any potential effects on the
flow from the pressure taps [43]. The internal galleries that led to the pressure taps came out through the side of the midsection of the airfoil. Hypodermic tubing was connected to the galleries and ran through one of the outer portions of the airfoil. Tygon tubing was connected to the hypodermic tubing, so that each individual pressure tap could be connected to its own pressure transducer. A photograph of the leading edge of the airfoil can be seen in Figure 2.4.

![Figure 2.4: Photograph of the leading edge of the SD7003 airfoil model from Sutton [40].](image)

Circular end plates, made out of aluminum, were installed on both ends of the airfoil to improve the mean spanwise uniformity of the flow [4]. The end plates had a diameter of 594 mm and were 2 mm thick. The outer edge of each endplate had a 30° chamfer. The airfoil and end plates were positioned in the tunnel so that they remained outside of the wind tunnel wall boundary layers. The airfoil was mounted vertically in the wind tunnel. The upper end plate had holes cut in it to allow the tygon tubing from the pressure taps to pass through. A specially designed ceiling panel and a modified floor panel were used to allow the rotation shaft of the airfoil to protrude from the wind tunnel. The rotation shaft allowed the airfoil to rotate about quarter chord. The lower portion of the rotation shaft sat in a bearing connected to the outside of the tunnel. The upper portion of the rotation shaft was connected to a Motion Group 5618M-0605SC stepper motor and a Thomson Micron 40:1 gearbox. A photograph of the airfoil setup in the wind tunnel can be seen in Figure 2.5.
Chapter 2. Experimental Details

2.3 Instrumentation

2.3.1 Surface Pressure Measurements

Surface pressure measurements were obtained simultaneously at all surface pressure tap locations using an array of pressure transducers. Two different arrays were used depending on the magnitude of the pressures being measured. One array consisting of All Sensors 0.5 INCH-D-MV millivolt pressure transducers was used to measure surface pressure for
Chapter 2. Experimental Details

Test cases at $Re_c \leq 150,000$, while the other array consisting of Freescale MPXV7002
0-2 kPa differential pressure transducers was used at $Re_c > 150,000$. Surface pressure
measurements were acquired using a Measurement Computing DaqBoard/3035USB data
acquisition card. A pitot-static probe connected to a Baratron MKS Type 120AD 1
torr/10 torr differential pressure transducer was used to measure the freestream dynamic
pressure, which was acquired using a National Instruments BNC-2110. For some of the
measurements an MKS Instruments Inc. 225AD 10 torr differential pressure transducer
was used to measure the freestream dynamic pressure instead due to the availability of
the Baratron transducer. A T-Type thermocouple connected to a National Instruments
SCC-68 signal conditioning module through a SCC-T02 thermocouple input was used to
measure the temperature inside the test section.

The total pressure from the pitot-static probe was used as the reference pressure,
$p_{ref}$, for the pressure transducer arrays. The total pressure was chosen as the reference
pressure because the transducers in each array could only measure accurately if a positive
voltage was read. This meant that each pressure transducer within each array read the
difference between the total freestream pressure, $p_{t,\infty}$, and the static pressure, $p_s$, from the
corresponding pressure tap on the airfoil. This difference is represented by the following
equation,

$$p_i = p_{t,\infty} - p_{s,i}. \quad (2.1)$$

With these pressure measurements, the coefficient of pressure, $C_p$, defined as,

$$C_p = \frac{p_s - p_{s,\infty}}{q_\infty}, \quad (2.2)$$

where $q_\infty$ is the freestream dynamic pressure, was calculated at each pressure tap. In
order to calculate $C_p$ with $p_i$ a modified equation had to be used. By substituting (2.1)
for $p_s$ in (2.2) and knowing that the freestream static pressure is equal to the difference
between the freestream total pressure and freestream dynamic pressure, the standard
equation for $C_p$ can be written as,

$$C_{p,i} = \frac{p_{t,\infty} - p_i - (p_{t,\infty} - q_\infty)}{q_\infty}, \quad (2.3)$$

which reduces to,

$$C_{p,i} = \frac{q_\infty - p_i}{q_\infty}. \quad (2.4)$$

The arrays were calibrated over the required test velocity range each day before use.
The transducers were calibrated against the Baratron MKS Type 120AD 1 torr/10 torr differential pressure transducer or the MKS Instruments Inc. 225AD 10 torr differential pressure transducer depending on which was being used that day. As with the surface pressure measurements the total pressure from the pitot-static probe was used as the reference pressure during the calibration. The static pressure from the pitot-static tube was fed to each transducer using a manifold for the calibrations.

Wake measurements were performed using the same pressure transducer arrays and a rake of total pressure tubes. The rake was mounted on a traverse system, so that wake measurements could be made across the entire width of the tunnel. A photograph of the setup used for the wake measurements can be seen in Figure 2.6. Depending on the angle of attack of the airfoil, multiple locations across the tunnel would need to be measured to capture the full wake. For smaller wakes at lower angles of attack, the rake was traversed slightly, so that the tubes would occupy the space between the tubes at the original location in order to improve the resolution of the wake measurements.

Figure 2.6: Photograph of the setup used for the wake measurements.


2.3.2 Oil Film Interferometry Measurements

Background

Due to the difficulties involved in measuring skin friction for flows containing separation bubbles, skin friction was measured using oil film interferometry (OFI). In order to measure the skin friction on a surface in an air flow, thin oil films are applied to the test surface in OFI. The three forces that lead to the motion of the oil film are gravity, the resulting pressure gradient from the air flow, and skin friction [42]. If the oil film is thin enough the effects from gravity and the pressure gradient are negligible, therefore OFI is based on the knowledge that oil under shear will spread at a rate related to the magnitude of the shear [13]. Squire [39] presented an equation describing the change in the thickness, $h$, of an oil sheet under shear over time, $t$:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\tau_{w, x} h^2}{2\mu} \right) + \frac{\partial}{\partial z} \left( \frac{\tau_{w, z} h^2}{2\mu} \right) = 0,$$

where $\tau_w$ is a shear stress and $\mu$ is the dynamic viscosity of the oil. This equation implies that the wall shear stress of a flow can be determined by measuring the changes in height of an oil distribution, of some known viscosity, over time.

Tanner and Blows were the first to implement oil film interferometry [42]. They were able to use Fizeau interferometry to determine changes in the height of an oil sheet. The interference process is illustrated in Figure 2.7. Commonly, a monochromatic light source is used to create an interference pattern in the oil sheet. Some of the light will reflect off the oil, while some will be transmitted through the oil and reflect off the surface of the model. The light that reflects off the surface of the model passes back through the oil and into the air. These out of phase beams of light constructively or destructively interfere when focused on an image plane. This interference process leads to the formation of fringe lines (the dark portions of an oil-flow pattern). Over time, as shear is applied to the oil, the spacing between the fringe lines increases. Figure 2.8 demonstrates the development of fringe lines over time.

Knowing the phase difference between two beams of light, $\phi$, the oil thickness can be calculated using,

$$h = \left( \frac{\lambda \phi}{4\pi} \right) \left( \frac{1}{\sqrt{n_f^2 - n_a^2\sin^2\theta_i}} \right),$$

where $\lambda$ is the wavelength of the incident light, $n_f$ is the oil index of refraction, $n_a$ is the air index of refraction, and $\theta_i$ is the incidence angle of the light [31]. With the oil thickness
Figure 2.7: The light interference process involved in oil film interferometry from Naughton et al. [31]

Figure 2.8: Fringe line development over time. The flow is from left to right.

calculated, the coefficient of skin friction, $C_f$, can be determined using various analysis techniques. The process outlined here is a single-image analysis technique implemented in MATLAB and was described by Naughton et al. [30]. Knowing the oil thickness, $C_f$ can be calculated at points of constructive and destructive interference in an interferogram using,

$$C_{f,i+1}^{1/2} = \frac{\int_0^x \left( n/C_f,i \right)^{1/2} dx}{h \sqrt{n} \int_0^t (q/\mu) dt},$$  \hspace{1cm} (2.7)$$

where $x$ is the distance from the leading edge of the oil, $n$ is the streamline divergence, $q$ is a reference dynamic pressure, and $i$ is the fringe line number. The initial solution is given by,

$$C_{f,1} = \frac{\mu x}{qht}.$$  \hspace{1cm} (2.8)
Photogrammetry

In order to analyze the interferograms the precise mapping of the two-dimensional image coordinates to the three-dimensional object coordinates needed to be determined. This mapping was done using photogrammetry. In this process the camera lens is represented by a single point known as the perspective centre located in three-dimensional space \((X_c, Y_c, Z_c)\) [25]. The camera orientation is also defined by three angles \((\omega, \phi, \kappa)\), which are associated with the pitch, yaw, and roll of the camera. The three space coordinates and three orientation angles defining the location and orientation of the camera are known as the exterior orientation parameters. The relationship between the perspective centre and the image coordinate system is characterized by the interior orientation parameters of the camera [25]. The main interior orientation parameters are the camera prinicipal distance and the photogrammetric prinicipal-point location. The relationship between the image plane and the model surface is illustrated in Figure 2.9.

![Figure 2.9: Illustration of the relationship between the image plane and the model surface from Naughton and Liu [29].](image-url)

A software package provided by Naughton et al. [30] was used to analyze the OFI images (interferograms). Naughton et al. [30] incorporated a two-step photogrammetry method in their software package. The first part of the method involves determining the interior orientation parameters and lens distortion parameters through the use of a calibration object. This calibration object has points of known coordinates marked on its surface. After an image has been captured of the calibration object, the reference points on the object can be identified in the image and linked to the physical location of the reference points on the object. Once the interior orientation parameters and lens
distortion parameters have been determined they remain valid until the camera system is adjusted. A typical calibration image is shown in Figure 2.10(a).

The exterior orientation parameters of the camera are determined in the second step of the photogrammetry process. This step involves identifying points of known location on the test surface in an image. The reference points could be built into the test surface or a grid of known points can be applied to the surface in order to determine the camera orientation. A typical calibration image of a grid with reference points is shown in Figure 2.10(b). If a grid is used, it must be removed after the second calibration image is captured, so that oil can be applied to the test surface. Each time the camera is moved or a different portion of the test surface is to be imaged the exterior orientation parameters need to be determined again.

![Typical calibration image](image1.jpg) ![Typical grid image](image2.jpg)

(a) Typical calibration image used to determine the interior orientation parameters. (b) Typical grid image used to determine the exterior orientation parameters.

Figure 2.10: Oil film interferometry calibration images used in the photogrammetry process.

**Practical Considerations and Uncertainties**

To achieve good quality fringe lines both the test surface and the lighting system must meet certain criteria. The defining characteristics of an ideal test surface include being very smooth, having constant optical properties, having the ability to be cleaned over the course of multiple uses, and having a resistance to scratching [48]. Zilliac [48] investigated different surfaces and coatings and their applicability for OFI. It was found that high flint content glass was the most suitable surface for OFI. It was also determined that the best materials or coatings to apply to a non-ideal test surface included ElectraMates Epoxy coating, black Ultem 1000 and Mylar. In terms of the lighting system, a monochromatic
light source should be used in order to achieve the best fringe contrast and also to improve
the accuracy of the skin friction analysis, since it is dependent on the wavelength of the
light being used [13]. As well, it is required that an extended light source be used so that
that the light hits the oil surface at varying angles of incidence, otherwise the fringe lines
will not be visible [48].

The main sources of uncertainty that arise in oil film interferometry include the oil
viscosity, photogrammetry inaccuracies, and precision uncertainties, namely uncertainties
caused by factors such as, electronic noise, the visibility of fringes, dust particles in the
fringe pattern, and imperfections in the test surface [31]. The uncertainty that arises
from the oil viscosity is due to knowing the oil viscosity and temperature precisely. Errors
associated with the startup and shutdown of the test facility have not been quantified,
however this source of uncertainty can be minimized by maximizing the time spent in a
state of constant shear during an OFI run. Other sources of error that contribute to the
overall uncertainty in the skin friction measurement include lens distortion errors and
errors in the measurement of freestream dynamic pressure [48].

**Experimental Setup**

The experimental setup used for the OFI measurements is shown in Figure 2.11. A
sodium lamp was used as a monochromatic light source and was mounted to the outer
frame of the tunnel facing the pressure side of the airfoil. White bristol board was used
as a diffuse reflector and was mounted on the outside of the tunnel windows facing the
suction side of the airfoil. With this lighting system, monochromatic light would pass
through the tunnel and reflect off the white bristol board causing the light to be directed
towards the suction side of the airfoil at varying angles. This ensures that light of varying
incidence angles would illuminate as much of the test surface as possible. Mylar film was
adhered to the surface of the airfoil using a modelling iron in order to make the test
surface optically smooth and partially reflective. Oil (Xiameter PMX-200 fluid) was
applied to the Mylar film using a putty knife. Three viscosities of oil were used, 10, 20
and 50 cSt, depending on the local shear stress magnitude. The physical properties of the
oil, provided by Dow Corning, can be found in Appendix A. The oil was applied in thin
slanted lines in order to maximize the coverage of the airfoil surface. Typically, multiple
lines of oil could be imaged at the same time based on the captured image size. A Stingray
F125B CCD camera was used to capture images of the oil-flow patterns on the suction
side of the airfoil. Multiple images were captured throughout a run. The temperature and
dynamic pressure within the test section were also measured using the same thermocouple
and pitot-static probe setup used for the surface pressure measurements. The time of a
run would vary depending on the local shear stress magnitude and the viscosity of oil being used, however the typical duration was approximately 10 minutes.

Figure 2.11: A photograph of the OFI setup used.

2.3.3 Hot-Wire Measurements

The hot-wire measurements were performed using a single-wire probe with a 5 µm copper plated tungsten wire. The probe was operated with a Newcastle constant temperature anemometer and an overheat ratio of 1.6. A National Instruments BNC-2110 was used for data acquisition. Data was sampled at 12,000 Hz for 60 seconds and low-pass filtered at 5,200 Hz. For these measurements the pitot-static probe within the tunnel was connected to an MKS Instruments Inc. 225AD 10 Torr differential pressure transducer and data was acquired using the National Instruments BNC-2110. The hot-wire probe was calibrated twice a day, once before the start of testing and once after to account for hot-wire drift. The hot-wire was calibrated over the range of velocities that were to be tested that day.
A King’s Law curve fit was used for the calibration. The drift was typically between 0.1% and 1.4% of $U$.

The hot-wire measurements were performed over top of the Mylar film that was adhered to the airfoil surface for the OFI measurements. This meant the hot-wire measurements were performed at a location 8 cm below midspan on the airfoil that corresponded to the same location on the airfoil that the OFI measurements were performed. With the use of the Mylar film, the reflection of the hot-wire probe could be used to determine the distance the probe was from the surface of the airfoil. This distance was determined by taking images of the hot-wire and its reflection and counting the pixels between the two. By traversing known distances, the change in pixels between the hot-wire and its reflection could be used to determine the distance the hot-wire was away from the surface of the airfoil. The hot-wire traverse system allowed the hot-wire to be traversed in the streamwise, spanwise, and wall-normal directions as well as rotated to adjust the angle between the probe and the surface of the airfoil. A photograph of the hot-wire setup can be seen in Figure 2.12.

Hot-wire measurements were performed at multiple locations along the airfoil chord, from just downstream of the leading edge to just past the point of reattachment, in order to track the development of flow instabilities and the transition process ahead of and throughout the laminar separation bubble. For each new chord location, the airfoil surface would be found again as detailed above. Approximately 40 points would be measured throughout the boundary layer profiles. The surface curvature of the airfoil and the angle of attack were taken into account for the steps the hot-wire would traverse to ensure that the path that the hot-wire followed was normal to the airfoil at that chord location. The first pass over the airfoil for each test case involved taking full boundary layer profiles at locations separated by approximately 0.05$c$. Once this coarse coverage of the airfoil was complete, the location of the peak in the fluctuations of the velocity within the boundary layer was determined along the airfoil. Hot-wire measurements were then performed around the locations of the peak in the velocity fluctuations between the full boundary layer profiles, in order to obtain a more complete coverage of the airfoil. For all measurements, the angle of the hot-wire probe from the airfoil surface was kept below 10° to limit the influence of the probe on the flow [7].
Figure 2.12: A photograph of the hot-wire setup used.
Chapter 3

Results and Discussion

3.1 Baseline Case

This section will focus on the measurements performed without a grid inside the tunnel grid holder, which corresponded to $T_u = 0.05\%$, and this case will herein be referred to as the baseline case. Surface pressure, skin friction and hot-wire measurements will be presented with the purpose of reviewing the laminar separation bubble behaviour for the SD7003 airfoil and relevant flow physics that will be examined further with the increased freestream turbulence intensity cases.

3.1.1 Surface Pressure

Surface pressure measurements for the baseline case were performed for the angles of attack, $\alpha$, and chord Reynolds numbers presented in Table 3.1. Coefficient of pressure distributions for several angles of attack at four Reynolds numbers are shown in Figure 3.1. The uncertainty on the $C_p$ measurements is smaller than the size of the symbols used in the figure (largest uncertainty was $\pm 0.01$), and are thus not included here. At $\alpha = 0^\circ$, the flow is fully attached on both the upper and lower surfaces of the airfoil, as indicated by the pressure on both surfaces recovering towards $C_p = 0$. With an increase in the angle of attack to $\alpha = 4^\circ$, the flow is not able to overcome the adverse pressure gradient on the upper surface of the airfoil and the flow separates at all Reynolds numbers. Downstream of separation, the separated shear layer transitions and the flow reattaches, leading to the formation of a laminar separation bubble at each Reynolds number. At $Re_c = 60,000$, the separation bubble is approximately $0.40c$ in length and can be termed a long bubble [41]. An increase in the Reynolds number causes the separation bubble to move towards the leading edge of the airfoil and decrease in length (approximately $0.1c$
Table 3.1: Test parameters for the surface pressure measurements for the baseline case.

<table>
<thead>
<tr>
<th>$T_u$[%]</th>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>60,000</td>
<td>$-5 \leq \alpha \leq 15$</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>$-5 \leq \alpha \leq 15$</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>$-5 \leq \alpha \leq 15$</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>$-5 \leq \alpha \leq 15$</td>
</tr>
</tbody>
</table>

in length at $Re_c = 250,000$). As expected, when the angle of attack is increased to $\alpha = 8^\circ$ at each Reynolds number the separation bubbles move towards the leading edge of the airfoil and decrease in length [3, 8, 10, 17]. At $Re_c = 60,000$, the flow over the upper surface of the airfoil stalls at $\alpha = 12^\circ$ as indicated by the presence of a pressure plateau just downstream of the leading edge that extends to the trailing edge. It can also be seen that as the Reynolds number increases to $Re_c = 250,000$ the stall angle increases to $14^\circ$.

Lift polars for the baseline case at the four Reynolds numbers can be seen in Figure 3.2. It can be seen that at $Re_c = 60,000$ there is a change in the slope of the lift polar around $\alpha = 2^\circ$. At that Reynolds number and angle of attack there is a laminar separation bubble present on the lower surface of the airfoil. With an increase in the angle of attack to $3^\circ$ the separation bubble is eliminated and the slope of the lift polar changes. Similarly, at $Re_c = 100,000$, the slope of the lift polar changes at $\alpha = 2^\circ$. As the Reynolds number increases, the stall angle and maximum lift coefficient increase. The decrease in lift post-stall is quite abrupt for Reynolds numbers of 60,000, 100,000 and 150,000. At $Re_c = 250,000$, the decrease in lift is slightly less abrupt due to the improved separation resistance at this Reynolds number. With an increase in the Reynolds number the boundary layer becomes more energetic which leads to enhanced separation resistance that leads to a more gradual decrease in lift post-stall.

The rest of the work presented in this section will focus on angles of attack of $4^\circ$ and $8^\circ$ due to the clear and distinctly different laminar separation bubbles (in terms of bubble size) that form at each Reynolds number and the fact that they have been studied previously [9, 17, 32, 36].

3.1.2 Skin Friction

Skin friction measurements were performed for the test cases presented in Table 3.2. Measurements at $Re_c = 60,000$ were attempted but good quality results could not be achieved due to the low magnitude of the shear stress on the surface of the airfoil. Distributions of the coefficient of skin friction for the baseline case at $Re_c = 150,000$ and
Figure 3.1: $C_p$ distributions for several angles of attack at $T_u = 0.05\%$. The markers on the select distributions represent pressure tap locations on the airfoil.

$Re_c = 250,000$ at two angles of attack, $\alpha = 4^\circ$ and $\alpha = 8^\circ$, are shown in Figure 3.3. The locations of separation and reattachment are identified on the plots and occur when $C_f = 0$. The use of OFI to characterize the separation bubble allowed for more accurate determination of the locations of separation and reattachment than those determined using pressure distributions. The reason for this is associated with the resolution of the separation bubble. With surface pressure measurements the resolution of the separation bubble is limited due to the spatial resolution of the pressure taps on the airfoil, while with the use of OFI measurements the entire bubble is visible, which makes it easier to determine exactly where the separation and reattachment points occur. The differences in uncertainty on $C_f$ can be attributed to the variable quality of fringe lines obtained and errors in determining the location of the leading edge of the oil line.
Figure 3.2: Lift polars for an SD7003 airfoil at four Reynolds numbers and $T_u = 0.05\%$.

Table 3.2: Test parameters for the oil film interferometry measurements for the baseline case.

<table>
<thead>
<tr>
<th>$T_u$ [%]</th>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>100,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.05</td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.05</td>
<td>250,000</td>
<td>4, 8</td>
</tr>
</tbody>
</table>

For each case, just upstream of reattachment a negative peak in $C_f$ occurs. This increase in the magnitude of skin friction is believed to correspond to the location of transition onset for the free shear layer [8]. The positive peak in skin friction just downstream of reattachment corresponds to the formation of a turbulent boundary layer. At $\alpha = 4^\circ$, skin friction measurements within the separation bubble were difficult to obtain, however the skin friction within the bubble is expected to display similar trends to the $\alpha = 8^\circ$ cases. With an increase in the angle of attack, both the positive and negative peak in skin friction increase in magnitude. The increase in the negative and positive skin friction peaks may be attributed to the increased local velocity outside the shear layer at higher angles of attack. The negative skin friction peak is larger in magnitude at $Re_c = 150,000$ for both angles of attack. A possible explanation for this could be the size of the region of recirculating flow within the separation bubble. At $Re_c = 150,000$, a larger separation bubble forms than at $Re_c = 250,000$. Therefore, at $Re_c = 150,000$, the free shear layer will move further away from the airfoil surface, which in turn may result in a greater contribution to wall-normal velocity near the location of transition onset due to the larger region of recirculating flow within the bubble.
3.1.3 Flow Velocity

Hot-wire measurements were performed for the test cases presented in Table 3.3. Mean boundary layer velocity profiles for the baseline case at $Re_c = 150,000$ and $Re_c = 250,000$ at $\alpha = 4^\circ$ and $\alpha = 8^\circ$ are shown in Figure 3.4. The points of separation and reattachment are identified on each plot with an $S$ and $R$, respectively. The start of each profile is identified with a dotted line and the dashed line corresponds to the normalized boundary layer thickness, $\delta/c$. Ahead of separation, the boundary layer profiles demonstrate the development of a laminar boundary layer for each case. After separation, reverse flow can be identified in the near wall region. A profile more representative of a turbulent boundary layer can be seen downstream of reattachment for each case as well, where a steep velocity gradient near the wall is followed by a gradual approach to the freestream velocity through the rest of the boundary layer, leading to a more full looking profile. The boundary layer thickness decreases with an increase in either the angle of attack or Reynolds number.

Table 3.3: Test parameters for the hot-wire measurements for the baseline case.

<table>
<thead>
<tr>
<th>$T_u$[%]</th>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.05</td>
<td>250,000</td>
<td>4, 8</td>
</tr>
</tbody>
</table>
Figure 3.4: Mean boundary layer velocity profiles for two Reynolds numbers at two angles of attack and $T_u = 0.05\%$. Separation and reattachment points are identified at the top of each plot and the dashed line corresponds to the boundary layer thickness.
The profiles of the RMS of the streamwise velocity fluctuations, $u'$, for the baseline case at $Re_c = 150,000$ and $Re_c = 250,000$ at $\alpha = 4^\circ$ and $\alpha = 8^\circ$ can be seen in Figure 3.5. The peak in the RMS velocity is large near the leading edge of the airfoil and decreases in magnitude over the airfoil up to the point of separation. Just past the point of separation, the RMS peak does not seem to noticeably change in magnitude. Further downstream, the RMS velocity grows rapidly leading up to the reattachment point. The RMS velocity decreases more gradually as the distance from the airfoil increases downstream of the point of reattachment compared to the profiles upstream of separation.

Plots of power spectral density for the fluctuating velocity signal taken at multiple locations along the chord of the airfoil at $Re_c = 150,000$ and two angles of attack $\alpha = 4^\circ$ and $\alpha = 8^\circ$ for the baseline case are shown in Figure 3.6. The measurements presented in Figure 3.6 were taken at the peak in the velocity fluctuations within the boundary layer. The spectra at each chord location have been offset by a magnitude proportional to $10^{x/c}$. At $Re_c = 150,000$ and $\alpha = 4^\circ$, the flow separates at $0.34c$ as indicated on the $C_f$ distribution. The fluctuating velocity spectra appear relatively flat leading up to and just past the point of separation indicating a lack of significant disturbance growth. A little further downstream of separation a broadband peak begins to develop around a normalized central instability frequency of 14. This broadband peak grows over the airfoil chord until the point of transition is reached. The point were the broadband peak disappears corresponds to the final breakdown to turbulence and this occurs rapidly (approximately over $0.03c$) [7]. Harmonics of the central instability frequency can also be seen just upstream of transition. It has been hypothesized that these harmonics develop because of the relatively high amplitude vertical velocity fluctuations around the point of transition [6]. With an increase in the angle of attack to $8^\circ$, the central instability frequency increases to a normalized frequency of 34 as expected [6]. At this angle of attack, the local velocity around the separated shear layer is larger and the separation bubble is thinner. This creates stronger wall-normal velocity gradients that cause the shear layer to roll-up at shorter intervals, leading to the increase in the central instability frequency. Again, harmonics of the central instability frequency are visible and the breakdown to turbulence occurs slightly more rapidly (approximately over $0.02c$) due to the increase in the disturbance growth rate associated with the increase in the angle of attack [6]. At this angle of attack, another peak is visible at a normalized frequency of 19.6. Peaks such as these that occur at a frequency lower than the central instability frequency have been identified in previous studies and attributed to bubble flapping, and it is believed to be the case here also [12, 14].
Figure 3.5: RMS boundary layer velocity profiles for two Reynolds numbers at two angles of attack and $T_u = 0.05\%$. Separation and reattachment points are identified at the top of each plot and the dashed line corresponds to the boundary layer thickness.
Figure 3.6: Spectra of the fluctuating velocity signal at \( Re_c = 150,000 \) for two angles of attack at \( T_u = 0.05\% \). The data shown was collected at the peak in the velocity fluctuations within the boundary layer.

Plots of power spectral density for the fluctuating velocity signal taken at multiple locations along the chord of the airfoil at \( Re_c = 250,000 \) and two angles of attack \( \alpha = 4^\circ \) and \( \alpha = 8^\circ \) for the baseline case are shown in Figure 3.7. The characteristics identified in Figure 3.6 can be seen in Figure 3.7 except at this Reynolds number the low frequency peak related to bubble flapping can be seen in the spectra taken at \( \alpha = 4^\circ \) not at \( \alpha = 8^\circ \). Table 3.4 presents the length and thickness of the bubble at each Reynolds number and angle of attack. It is evident that bubble flapping is present for the cases with similar bubble length and thickness. Possibly, these separation bubbles are more unstable at the given Reynolds number and angle of attack, while the longer and shorter separation bubbles at \( Re_c = 150,000 \) and \( \alpha = 4^\circ \) and at \( Re_c = 250,000 \) and \( \alpha = 8^\circ \) are more stable, so bubble flapping is not evident. It can also be seen that the central instability frequency increased to a normalized frequency of 17 at \( \alpha = 4^\circ \) and 39 at \( \alpha = 8^\circ \) with an increase in the Reynolds number. At the higher Reynolds number, the separation bubble is thinner, which causes the separated shear layer to roll-up at shorter intervals, similar to the effect of an increase in angle of attack. Another peak is also present at a normalized frequency of 10 for both angles of attack. At each angle of attack, this peak is of similar magnitude at each location along the chord when the offset applied to the spectra is removed, leading to the conclusion that this peak is caused by vibration in the hot-wire setup.
Table 3.4: Bubble length and thickness for the baseline cases.

<table>
<thead>
<tr>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
<th>Bubble Length [$x/c$]</th>
<th>Bubble Thickness [$y/c$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150,000</td>
<td>4</td>
<td>0.26</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.14</td>
<td>0.011</td>
</tr>
<tr>
<td>250,000</td>
<td>4</td>
<td>0.16</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.10</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Figure 3.7: Spectra of the fluctuating velocity signal at $Re_c = 250,000$ for two angles of attack at $T_u = 0.05\%$. The data shown was collected at the peak in the velocity fluctuations within the boundary layer.

3.2 Effect of Freestream Turbulence

This section will focus on the measurements performed at the increased freestream turbulence intensities. Surface pressure, skin friction and hot-wire measurements will be presented to establish the effects freestream turbulence intensity has on the laminar separation bubble and flow transition over an SD7003 airfoil.

3.2.1 Surface Pressure

Surface pressure measurements for the increased freestream turbulence intensity cases were performed for the angles of attack and chord Reynolds numbers presented in Table 3.5. $C_p$ distributions at $\alpha = 4^\circ$ for the four Reynolds numbers and four freestream turbulence intensities are shown in Figure 3.8. The baseline case was also included for comparison. It can be seen that the laminar separation bubble that was present on the upper surface of the airfoil for the baseline case is completely eliminated with an increase
Table 3.5: Test parameters for the surface pressure measurements with increased freestream turbulence intensity.

<table>
<thead>
<tr>
<th>$T_u$ [%]</th>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>60,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td>0.34</td>
<td>60,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td>0.70</td>
<td>60,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td>0.99</td>
<td>60,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>-5 ≤ $\alpha$ ≤ 15</td>
</tr>
</tbody>
</table>

in freestream turbulence intensity to just 0.17% for each Reynolds number. This result is perhaps unexpected since a separation bubble has been identified at this angle of attack and a Reynolds number of 60,000 for a turbulence intensity of 1% before [9]. As well, this result further establishes how difficult it is to study laminar separation bubbles across different facilities. Further increases in turbulence intensity do not result in significant changes to the pressure distributions. Although the separation bubble has been eliminated with the increase in turbulence intensity, a slight kink in the pressure distributions remains visible. This slight kink has been documented by other researchers and attributed to laminar to turbulent transition within an attached boundary layer and has been found to be the case here as well [40].

$C_p$ distributions at $\alpha = 8^\circ$ for the four Reynolds numbers and the five freestream turbulence intensities are shown in Figure 3.9. At this angle of attack, an increase in freestream turbulence intensity to 0.17% does not eliminate the separation bubble found in the baseline case, but significantly reduces the size of the separation bubble for all Reynolds numbers except $Re_c = 250,000$ (approximately 50% at $Re_c = 60,000$, 40% at $Re_c = 100,000$, and 30% at $Re_c = 150,000$). This occurs because the increase in freestream turbulence intensity promotes an earlier transition, which causes the separated shear layer to remain closer to the airfoil surface and leads to a reattachment point
Figure 3.8: $C_p$ distributions for five freestream turbulence intensities at four Reynolds numbers and $\alpha = 4^\circ$. The markers on the distributions represent pressure tap locations on the airfoil.

located closer to the leading edge of the airfoil. At $Re_c = 60,000$, a further increase in freestream turbulence intensity to 0.34% leads to a slight reduction of the laminar separation bubble present at $T_u = 0.17\%$. Further increases in turbulence intensity to 0.99% does not significantly change the pressure distributions. At $Re_c = 100,000$ and $Re_c = 150,000$, increases in freestream turbulence intensity above 0.17% does not lead to significant changes to the pressure distributions. Overall, the effect of increasing turbulence intensity decreases as Reynolds number increases because at higher Reynolds numbers the boundary layer is already at a more energetic state, so adding additional energy into the boundary layer with increases in freestream turbulence intensity does not have as great of an effect on the laminar separation bubble.
Figure 3.9: $C_p$ distributions for five freestream turbulence intensities at four Reynolds numbers and $\alpha = 8^\circ$. The markers on the distributions represent pressure tap locations on the airfoil.

Lift polars for the cases just discussed are presented in Figure 3.10. At increased turbulence intensities, a more energetic turbulent boundary layer forms over the airfoil, which has better separation resistance than the boundary layer that forms at $T_u = 0.05\%$ and contributes to improvements in aerodynamic performance. As the turbulence intensity increases, the maximum lift coefficient for the airfoil increases, which has been documented before [44]. At $Re_c = 100,000$, the maximum lift coefficient increases from $c_l = 1.09$ for the baseline case to $c_l = 1.20$ when $T_u = 0.99\%$. Similarly, as the turbulence intensity increases the stall angle increases (at $Re_c = 100,000$, $\alpha_{c_{\text{max}}} = 11^\circ$ at $T_u = 0.05\%$ to $\alpha_{c_{\text{max}}} = 12^\circ$ at $T_u = 0.99\%$). Post-stall, the decrease in lift is less abrupt at increased turbulence intensities compared to the baseline case. The slope change in the baseline lift
polar at $Re_c = 60,000$ and $Re_c = 100,000$ (Figures 3.10(a) and (b)) around $\alpha = 2^\circ$ that was mentioned previously is eliminated with an increase in the freestream turbulence intensity. As with the pressure distributions, at higher Reynolds numbers the effects of freestream turbulence intensity are less significant.

![Graphs showing lift polars for different Reynolds numbers with varying freestream turbulence intensities.]

Figure 3.10: Lift polars for an SD7003 airfoil at four Reynolds numbers for five freestream turbulence intensities.

### 3.2.2 Skin Friction

Skin friction measurements were performed for the test cases presented in Table 3.6. Coefficient of skin friction distributions for $Re_c = 150,000$ at $\alpha = 4^\circ$ and $\alpha = 8^\circ$ and freestream turbulence intensities of 0.05%, 0.17%, 0.34%, and 0.99% are presented in Figure 3.11. At $\alpha = 4^\circ$ (Figure 3.11(a)), the separation bubble is eliminated at each
Table 3.6: Test parameters for the oil film interferometry measurements with increased freestream turbulence intensity.

<table>
<thead>
<tr>
<th>$T_u\ [%]$</th>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>100,000</td>
<td>4, 8</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.34</td>
<td>100,000</td>
<td>4, 8</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.99</td>
<td>100,000</td>
<td>4, 8</td>
</tr>
<tr>
<td></td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td></td>
<td>250,000</td>
<td>4, 8</td>
</tr>
</tbody>
</table>

increased turbulence intensity, as seen in the pressure distributions. Transition also occurs earlier along the airfoil chord for the increased turbulence intensity cases compared to the baseline case. Although transition starts earlier for the cases with increased turbulence intensity, the distance between the minimum and second positive peak in skin friction is smaller for the baseline case ($\approx 10\%$ chord versus $\approx 17\%$ chord), indicating that the presence of a separation bubble results in a more rapid development of a turbulent boundary layer downstream of the minimum value in skin friction. The peak in $C_f$ corresponding to the start of a turbulent boundary layer was very similar for each turbulence intensity. Comparing the increased freestream turbulence intensity cases it can be seen that the boundary layer behaviour upstream and downstream of transition appears very similar even though as the turbulence intensity increases the flow transitions slightly earlier. This suggests that the earlier onset of transition for each increase in freestream turbulence intensity does not significantly affect the turbulent boundary layer that forms downstream of transition.

At $\alpha = 8^\circ$ (Figure 3.11(b)), a separation bubble is still present for the increased freestream turbulence intensity cases. Examining the skin friction distributions, it is clear that the separation bubble for $T_u = 0.99\%$ is slightly smaller than the separation bubble at $T_u = 0.34\%$, which is slightly smaller than the separation bubble at $T_u = 0.17\%$. With the increases in freestream turbulence intensity transition is promoted, which causes the vortices in the separated shear layer to form sooner. This in turn leads to a shorter and thinner laminar separation bubble, which will be shown by the hot-wire measurements in the next section. This observation was not something that could be determined with any certainty from the pressure distributions. This highlights the usefulness of skin friction measurements to accurately characterize the separation bubble. The magnitude of the
negative peak in skin friction decreases as turbulence intensity increases, most likely due to the formation of a smaller, less energetic separation bubble. The second positive peak in skin friction decreases with an increase in turbulence intensity. At this angle of attack, it is clear that an increase in turbulence intensity results in an increase in the distance between the minimum and second positive peak in skin friction. It can also be seen that the boundary layer behaviour downstream of the second positive peak is very similar for all four turbulence intensities even though the larger turbulence intensities result in an earlier transition.

Figure 3.11: $C_f$ distributions for $Re_c = 150,000$ at two angles of attack and four freestream turbulence intensities. × and ◆ markers identify points of separation and reattachment.

Coefficient of skin friction distributions for $Re_c = 250,000$ at $\alpha = 4^\circ$ and $\alpha = 8^\circ$ and freestream turbulence intensities of 0.05%, 0.17%, 0.34%, and 0.99% are presented in Figure 3.12. At $\alpha = 4^\circ$ (Figure 3.12(a)), the separation bubble is eliminated due to the increase in turbulence intensity. The second positive peak in skin friction is the same for the increased turbulence intensities and as turbulence intensity increases an earlier transition is promoted. As with the cases at $Re_c = 150,000$ and $\alpha = 8^\circ$ (Figure 3.11(b)), downstream of the second positive peak the boundary layer exhibits the same behaviour for each of the increased turbulence intensities. Again, the distance between the minimum and second positive peak in skin friction is larger for the cases without a separation bubble.

At $\alpha = 8^\circ$ (Figure 3.12(b)), a separation bubble is present for each freestream turbulence intensity. Similarly to the cases at $Re_c = 150,000$ and $\alpha = 8^\circ$ (Figure 3.11(b)), the negative peak in skin friction decreases in magnitude with an increase in the turbu-
lence intensity above 0.05%. Furthermore, downstream of the second positive peak, the boundary layer exhibits similar behaviour for each turbulence intensity.

Figure 3.12: $C_f$ distributions for $Re_c = 250,000$ at two angles of attack and four freestream turbulence intensities. × and ◢ markers identify points of separation and reattachment.

3.2.3 Flow Velocity

Hot-wire measurements were performed for the test cases presented in Table 3.7. Mean boundary layer velocity profiles for $Re_c = 150,000$ and $Re_c = 250,000$ at $\alpha = 8^\circ$ and two freestream turbulence intensities, $T_u = 0.17\%$ and $T_u = 0.99\%$, are shown in Figure 3.13. With an increase in the turbulence intensity the boundary layer thickness has decreased for both Reynolds numbers, however the profiles look very similar to the baseline case. Laminar boundary layer development is evident upstream of separation, reverse flow can be identified in the near wall region past the separation point, and a turbulent profile can be seen downstream of reattachment. In order to compare the shape of the mean boundary layer velocity profiles upstream of separation for the different turbulence intensities, the profiles at $x/c = 0.03$ for $Re_c = 150,000$ and $Re_c = 250,000$ were plotted against one another in Figure 3.14. The shape of the profiles are similar for each turbulence intensity at each Reynolds number. All of the profiles approach maximum velocity linearly and the decrease in slope with an increase in freestream turbulence intensity is very small.
Figure 3.13: Mean boundary layer velocity profiles for two Reynolds numbers and two freestream turbulence intensities at $\alpha = 8^\circ$. Separation and reattachment points are identified at the top of each plot and the dashed line corresponds to the boundary layer thickness.
Table 3.7: Test parameters for the hot-wire measurements with increased freestream turbulence intensity.

<table>
<thead>
<tr>
<th>$T_u [%]$</th>
<th>$Re_c$</th>
<th>$\alpha$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.17</td>
<td>250,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.99</td>
<td>150,000</td>
<td>4, 8</td>
</tr>
<tr>
<td>0.99</td>
<td>250,000</td>
<td>4, 8</td>
</tr>
</tbody>
</table>

Figure 3.14: Mean boundary layer velocity profiles for two Reynolds numbers and three freestream turbulence intensities at $\alpha = 8^\circ$ and $x/c = 0.03$.

The profiles of the RMS of the streamwise velocity fluctuations for $Re_c = 150,000$ and $Re_c = 250,000$ at $\alpha = 8^\circ$ and two freestream turbulence intensities, $T_u = 0.17\%$ and $T_u = 0.99\%$, are shown in Figure 3.15. As with the mean profiles, the RMS profiles are very similar to the baseline case for both Reynolds numbers. A decrease in the RMS peak between the leading edge and the point of separation is evident, just past the point of separation there is no noticeable growth in the RMS peak, and just upstream of reattachment the RMS velocity increases rapidly.
Figure 3.15: RMS boundary layer velocity profiles for two Reynolds numbers and two freestream turbulence intensities at $\alpha = 8^\circ$. Separation and reattachment points are identified at the top of each plot and the dashed line corresponds to the boundary layer thickness.
The development of the maximum RMS velocity along the chord of the airfoil for $Re_c = 150,000$ and $Re_c = 250,000$ at $\alpha = 8^\circ$ and $T_u = 0.05\%$, $T_u = 0.17\%$ and $T_u = 0.99\%$ is shown in Figure 3.16. At $Re_c = 150,000$, the maximum RMS velocity is relatively low upstream of separation and decreases along the chord past the separation point for each case. A little further downstream of the separation point, the RMS velocity reaches a minimum before starting to increase rapidly. This rapid increase in RMS velocity signifies the start of the transition process, and starts earlier with an increase in the freestream turbulence intensity. A peak velocity is reached near the reattachment point, and this peak is similar in magnitude for each turbulence intensity. The maximum RMS velocity then begins to decrease in the attached turbulent boundary layer for each case. The trend in the maximum RMS velocity described here is qualitatively similar to the findings in previous separation bubble studies [6, 45]. The same trend in the maximum RMS velocity can be seen in the cases at $Re_c = 250,000$, however there does appear to be significant data scatter for $T_u = 0.99\%$ and the RMS velocity is much larger ahead of the separation point for each turbulence intensity.

![Figure 3.16: Development of the maximum RMS velocity along the airfoil chord for two Reynolds numbers and three freestream turbulence intensities at $\alpha = 8^\circ$.](image)

Plots of power spectral density for the fluctuating velocity signal taken at multiple locations along the chord of the airfoil at $Re_c = 150,000$ at two angles of attack $\alpha = 4^\circ$ and $\alpha = 8^\circ$ for $T_u = 0.17\%$ and $T_u = 0.99\%$ are shown in Figure 3.17. At $\alpha = 4^\circ$ (Figure 3.17(a) and (c)), the separation bubble is eliminated for each turbulence intensity as evidenced by the lack of a central instability frequency that dominates the transition process within the separated shear layer. Instead, a more gradual transition from an attached laminar boundary layer to a turbulent boundary layer can be seen. With an...
increase in angle of attack to $\alpha = 8^\circ$, the spectra show the same gradual transition however over a shorter distance along the airfoil, even though there is still a laminar separation bubble present for both turbulence intensities.

To investigate the change in the velocity spectra between the baseline case and the increased turbulence cases at $\alpha = 8^\circ$, the velocity-time series of the fluctuating velocity component at the point of separation for all turbulence intensities were compared. The velocity time-series for $T_u = 0.05\%$, $T_u = 0.17\%$ and $T_u = 0.99\%$ are shown in Figures 3.18, 3.19 and 3.20. The derivative of the fluctuating velocity component with respect to time and the skewness of the velocity derivative are also included. The baseline velocity time-series is indicative of a laminar boundary layer, since it contains relatively
moderate velocity fluctuations (approximately $0.2U_{\infty}$) and no signs of intermittent spiking in the derivative of the velocity time-series. The velocity time-series at $T_u = 0.17\%$ is quite similar. The velocity fluctuations are of similar magnitude to the baseline case, and no signs of intermittent spiking are visible. At $T_u = 0.99\%$, the velocity time-series still display fluctuations of a similar magnitude, however the skewness of the velocity derivative appears more intermittent. These findings coupled with the shape of the boundary layer profiles ahead of separation, seem to indicate that a laminar boundary layer is still present upstream of separation for the increased turbulence cases.

![Figure 3.18: Velocity time-series of the fluctuating velocity component at the point of separation for $Re_c = 150,000$ at $\alpha = 8^\circ$ and $T_u = 0.05\%$. The derivative of the fluctuating velocity signal with respect to time and the skewness of the velocity derivative are also included.](image)

In order to further investigate the differences between the spectra for each angle of attack at each freestream turbulence intensity, the spectra around the separation point and reattachment point for all three freestream turbulence intensities were plotted in Figure 3.21. These spectra were plotted without an offset applied in order to identify the differences between each case. If spectra were not available at the separation or reattachment point then spectra at a location just downstream of the separation and reattachment point were used. For the cases without a laminar separation bubble ($Re_c = 150,000$ at $\alpha = 4^\circ$ for $T_u = 0.17\%$ and $T_u = 0.99\%$), the spectrum at the minimum in the coefficient of skin friction was used for a comparative spectrum for the separation point and the spectrum at a similar location in the skin friction distribution as the
Figure 3.19: Velocity time-series of the fluctuating velocity component at the point of separation for \( Re_c = 150,000 \) at \( \alpha = 8^\circ \) and \( T_u = 0.17\% \). The derivative of the fluctuating velocity signal with respect to time and the skewness of the velocity derivative are also included.

Figure 3.20: Velocity time-series of the fluctuating velocity component at the point of separation for \( Re_c = 150,000 \) at \( \alpha = 8^\circ \) and \( T_u = 0.99\% \). The derivative of the fluctuating velocity signal with respect to time and the skewness of the velocity derivative are also included.
reattachment point of the baseline case was used for a comparative spectrum at the point of reattachment.

At $\alpha = 4^\circ$, the spectra across the three turbulence intensities are quite different at the point of separation. The baseline case displays a very flat spectrum, while the increased turbulence intensity cases display spectra that are close to being fully turbulent. The spectra at reattachment are very similar for all three freestream turbulence intensities.

At $\alpha = 8^\circ$, the spectra at separation for $T_u = 0.05\%$ is relatively flat again, however there is more energy at lower frequencies than at the lower angle of attack. The spectra at $T_u = 0.17\%$ and $T_u = 0.99\%$ are still more turbulent than the baseline spectrum, however not to the same degree as the spectra at $\alpha = 4^\circ$. This seems to indicate that at $\alpha = 4^\circ$, the increase in freestream turbulence intensity above $T_u = 0.05\%$ adds sufficient energy to the laminar boundary layer to initiate transition to turbulence before the boundary layer has a chance to separate, thus eliminating the separation bubble. At $\alpha = 8^\circ$ however, the increase in freestream turbulence intensity does not add sufficient energy to the laminar boundary layer to prevent separation. This still does not explain why the spectra at $\alpha = 8^\circ$ do not display a central instability frequency. It is possible that the increase in freestream turbulence intensity diminishes the prominence of the central instability frequency in the spectra, or in other words, the energy content of the spectra is so much larger that the central instability frequency is indistinguishable from the rest of the spectra. A similar occurrence has been documented for the shedding peak in the wake behind a wall-mounted cube subjected to increases in freestream turbulence intensity [19].

In order to further explore this hypothesis, the freestream turbulence spectra for the grids are shown again in Figure 3.22, but the range of normalized frequency that the shear layer instability occurs over for the baseline case is identified with dashed lines. It is clear that the energy content of the spectra is significantly different for the increased freestream turbulence intensity cases compared to the baseline case over the range of normalized frequency where the shear layer instability is present. The baseline case has very little energy content over that frequency range, while the increased freestream turbulence intensity cases have a full turbulent energy profile. Taking into account the shape of the mean boundary layer velocity profiles, the development of the RMS velocity over the airfoil, the velocity time-series at separation and the freestream turbulence spectra, it seems plausible that the prominence of the central instability frequency has been diminished with an increase in freestream turbulence intensity. In order to validate this hypothesis, flow field measurements should be performed for the test cases presented here.
Figure 3.21: Spectra of the fluctuating velocity signal at $Re_c = 150,000$ for two angles of attack and three freestream turbulence intensities around the separation and reattachment locations. For the increased turbulence intensity cases there is no separation bubble at $\alpha = 4^\circ$. For these cases the location of minimum $C_f$ was used as a comparative spectrum for the separation location and the spectrum at a similar location in the skin friction distribution as the reattachment point for the baseline case was used as the comparative spectrum for the reattachment location.

Plots of power spectral density for the fluctuating velocity signal taken at multiple locations along the chord of the airfoil at $Re_c = 250,000$ and two angles of attack $\alpha = 4^\circ$ and $\alpha = 8^\circ$ for $T_u = 0.17\%$ and $T_u = 0.99\%$ are shown in Figure 3.23. At this Reynolds number, the spectra look very similar to the $Re_c = 150,000$ cases. It can be seen that the peak around a normalized frequency of 10 that corresponds to vibration in the hot-wire setup is drowned out for $T_u = 0.99\%$.

The velocity time-series of the fluctuating velocity component at the point of separation for $T_u = 0.05\%$, $T_u = 0.17\%$ and $T_u = 0.99\%$ are shown in Figures 3.24, 3.25 and 3.26. These velocity time-series have larger fluctuations than the cases at $Re_c = 150,000$. Again, the velocity time-series at $T_u = 0.05\%$ and $T_u = 0.17\%$ are not very intermittent, while the velocity time-series at $T_u = 0.99\%$ is more intermittent. As with the cases at $Re_c = 150,000$, these findings and the shape of the boundary layer profiles upstream of separation seem to indicate the presence of a laminar boundary layer at the point of separation.

The spectra around the separation point and the reattachment point for freestream turbulence intensities of 0.05\%, 0.17\% and 0.99\% at $Re_c = 250,000$ and two angles of attack $\alpha = 4^\circ$ and $\alpha = 8^\circ$ are shown in Figure 3.27. Again, no offset has been applied to the spectra to make comparisons easier. The spectra are very similar to the cases
Figure 3.22: Power spectral density plots of velocity for each grid at the leading edge of the airfoil at $Re_c = 150,000$. The frequency range of the shear layer instability is identified by the dashed lines.

at $Re_c = 150,000$, indicating an elevated energy content in the spectra for the increased turbulence cases compared to the baseline case. As with the cases at $Re_c = 150,000$, these spectra indicate that the increase in freestream turbulence intensity introduces enough energy to the laminar boundary layer to initiate transition before the flow separates at $\alpha = 4^\circ$, while at $\alpha = 8^\circ$ the increase in freestream turbulence intensity does not provide enough energy to prevent separation. Again, the spectra at the reattachment point are very similar for each turbulence intensity.
Figure 3.23: Spectra of the fluctuating velocity signal at $Re_c = 250,000$ for two angles of attack and two freestream turbulence intensities. The data shown was collected at the peak in the velocity fluctuations within the boundary layer.
Figure 3.24: Velocity time-series of the fluctuating velocity component at the point of separation for $Re_c = 250,000$ at $\alpha = 8^\circ$ and $T_u = 0.05\%$. The derivative of the fluctuating velocity signal with respect to time and the skewness of the velocity derivative are also included.

Figure 3.25: Velocity time-series of the fluctuating velocity component at the point of separation for $Re_c = 250,000$ at $\alpha = 8^\circ$ and $T_u = 0.17\%$. The derivative of the fluctuating velocity signal with respect to time and the skewness of the velocity derivative are also included.
Figure 3.26: Velocity time-series of the fluctuating velocity component at the point of separation for $Re_c = 250,000$ at $\alpha = 8^\circ$ and $T_u = 0.99\%$. The derivative of the fluctuating velocity signal with respect to time and the skewness of the velocity derivative are also included.

Figure 3.27: Spectra of the fluctuating velocity signal at $Re_c = 250,000$ for two angles of attack and three freestream turbulence intensities around the separation and reattachment locations. For the increased turbulence intensity cases there is no separation bubble at $\alpha = 4^\circ$. For these cases the location of minimum $C_f$ was used as a comparative spectrum for the separation location and the spectrum at a similar location in the skin friction distribution as the reattachment point for the baseline case was used as the comparative spectrum for the reattachment location.
Chapter 4

Conclusions and Recommendations

A study on the laminar separation bubble and flow transition process over an SD7003 airfoil was conducted in the low speed wind tunnel at the University of Toronto Institute for Aerospace Studies. Surface pressure, skin friction and hot-wire measurements were performed for Reynolds numbers ranging from 60,000 to 250,000, over a range of angles of attack and for five freestream turbulence intensities between 0.05% and 0.99%. Angles of attack of 4° and 8° were studied in depth. Turbulence-generating grids were used to produce the turbulence intensities required for the measurements.

A laminar separation bubble on the upper surface of the airfoil was present for all test cases at $T_u = 0.05\%$, the baseline case. With an increase in the turbulence intensity to just 0.17% the separation bubble was eliminated for all Reynolds numbers at $\alpha = 4^\circ$. At $\alpha = 8^\circ$, the laminar separation bubble was not eliminated with an increase in freestream turbulence intensity to 0.17% but was significantly reduced in size at all Reynolds numbers other than 250,000. Increases in freestream turbulence intensity above 0.17% were not found to significantly affect the pressure distributions.

An increase in freestream turbulence intensity above the baseline case led to improvements in aerodynamic performance of the airfoil, since a more energetic turbulent boundary layer formed over the airfoil. The maximum lift coefficient and stall angle were found to increase with increasing freestream turbulence intensity. As well, the decrease in lift post-stall was less abrupt at the larger freestream turbulence intensities.

The skin friction measurements displayed a negative peak in skin friction just upstream of reattachment and a positive peak just downstream of reattachment, corresponding to the formation of a turbulent boundary layer. Both the negative peak and positive peak in skin friction were found to increase in magnitude with an increase in angle of attack. It was found that boundary layers with a separation bubble displayed a more rapid development of a turbulent boundary layer downstream of the minimum
in skin friction even though transition started earlier for the cases without a separation bubble. The increased freestream turbulence intensity cases all displayed similar behaviour and magnitudes in skin friction downstream of the peak corresponding to the formation of a turbulent boundary layer, suggesting the earlier transition promoted by the increase in freestream turbulence intensity did not significantly affect the turbulent boundary layer forming downstream of transition. The magnitude of the negative peak in skin friction was found to decrease as turbulence intensity increased.

The mean and RMS boundary layer velocity profiles for cases that contained a laminar separation bubble were similar for each turbulence intensity. The velocity time-series at separation for each case that contained a laminar separation bubble and the shape of the boundary layer profiles upstream of separation indicated the presence of a laminar boundary layer. The fluctuating velocity spectra for the baseline case displayed a broadband peak focused around a central instability frequency just downstream of the point of separation that increased with both angle of attack and Reynolds number. Harmonics of the central instability frequency were also identified. A peak at a normalized frequency less than the central instability frequency was found for cases with similar bubble length and thickness and attributed to bubble flapping. The fluctuating velocity spectra for the increased freestream turbulence intensity cases displayed a gradual transition from a laminar to turbulent boundary layer without a central instability frequency for the cases where the laminar separation bubble was eliminated. Interestingly, the same was found for the cases with laminar separation bubbles. The spectra for all the turbulence intensities investigated around the separation point and reattachment point were plotted to further investigate. It was found that at both angles of attack the baseline case displayed a relatively flat spectrum at separation. The increased freestream turbulence intensity cases with a separation bubble were found to contain more energy than the baseline case. It was hypothesized that the increase in freestream turbulence intensity diminishes the prominence of the central instability frequency relative to the rest of the spectra.

Based on the findings of this study the following recommendations for future work are proposed:

1. Since various measurement techniques were used to characterize the laminar separation bubble and to study the transition of the flow over the SD7003 airfoil it was difficult to obtain good data for the test cases of interest across all of the measurement techniques. Firstly, the freestream turbulence intensities used eliminated the laminar separation bubble for the Reynolds numbers investigated at $\alpha = 4^\circ$. These Reynolds numbers were chosen based on issues associated with the measurement techniques. It was difficult to obtain useable data within the laminar separation
bubbles at Reynolds numbers lower than 100,000 with the oil film interferometry measurements on the 3D printed airfoil model, while vibrations in the hot-wire setup were noticeable in the data at $Re_c = 250,000$. As well, PIV measurements were attempted to get a sense of the flow field, however the test cases that yielded good results for the oil film interferometry measurements made it very difficult to obtain useable data with PIV measurements due to the surface curvature of the airfoil and the thinness of the boundary layer. Therefore, it is recommended that before future experiments are performed the experimental setup and techniques used should be optimized for the test cases of interest, which leads into the second recommendation.

2. It is recommended that the airfoil model used in the study be redesigned with oil film interferometry measurements in mind. The finish on the 3D printed surface made it difficult to obtain useable data within the laminar separation bubble at $\alpha = 4^\circ$ and at Reynolds numbers lower than 100,000 even with the application of Mylar film. With a machined surface, or at the very least a modified surface on the 3D printed model, collecting skin friction data at lower Reynolds numbers and angles of attack would be possible, making it easier to also perform measurements investigating the flow field.

3. In order to confirm whether the increase in freestream turbulence intensity above $T_u = 0.05\%$ diminished the prominence of the central instability frequency, measurements investigating the flow field should be performed. A measurement technique such as PIV or smoke wire flow visualizations could be used. Another option could be to design an airfoil with surface pressure microphones, so that spectra of the fluctuating surface pressure could be studied. It would be interesting to see if the increase in freestream turbulence intensity affected the surface pressure and hot-wire measurements the same way, or if one technique is better to use when studying the effects of grid generated turbulence for the cases investigated here.
Appendix A

Dow Corning 200 Fluid Properties
Table 1: Typical properties of viscosity grades.
These values are not intended for use in preparing specifications.

<table>
<thead>
<tr>
<th>Viscosity at 25°C mm²/s (cSt)</th>
<th>Flash Point, closed cup °C</th>
<th>Flash Point, open cup °C</th>
<th>Specific Gravity at 25°C</th>
<th>Viscosity Temperature Coefficient</th>
<th>Coefficient of Volume Expansion, 1/K</th>
<th>Refractive Index at 25°C</th>
<th>Surface Tension at 25°C cm/Hg</th>
<th>Thermal Conductivity at 50°C W/mK</th>
<th>Boil Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65</td>
<td>-3.0°C</td>
<td>-68°C</td>
<td>0.761</td>
<td>0.31</td>
<td>0.00134</td>
<td>1.375</td>
<td>15.9</td>
<td>0.100</td>
<td>100°C at 760 mm</td>
</tr>
<tr>
<td>1.0</td>
<td>34.4°C</td>
<td>-100°C</td>
<td>0.818</td>
<td>0.41</td>
<td>0.00134</td>
<td>1.382</td>
<td>17.4</td>
<td>-</td>
<td>152°C at 760 mm</td>
</tr>
<tr>
<td>5.0</td>
<td>&gt;100°C</td>
<td>135°C</td>
<td>0.920</td>
<td>0.55</td>
<td>0.00105</td>
<td>1.397</td>
<td>19.7</td>
<td>-</td>
<td>120-160°C at 0.5ppm VOLATILITY</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% max weight loss after 24 hrs at 150°C</td>
</tr>
</tbody>
</table>

1. CTM 0004
2. CTM 0021
3. CTM 0006
4. CTM 0033. Due to the effects of supercooling, this test method yields very points lower than the temperatures at which those silicone fluids solidify when held at such temperatures for a longer period.
5. CTM 0001A
6. CTM 0747 (1 - (Viscosity at 99°C / Viscosity at 38°C))
7. CTM 0420
8. CTM 0002
9. CTM 0461
11. CTM 208. Determined by heating a 2 gram sample in a 50 millilitre beaker for 24 hours at 150°C. The heating is carried out in an air circulating oven.

Figure 1: Viscosity temperature slopes for DOW CORNING 200 Fluids and some petroleum oils.
Bibliography


