Investigation of laminar separation bubble behavior under unsteady flows using PIV and Thermal Imaging Methods

Faegheh Ghorbanishohrat¹, Farid Samara¹, David A. Johnson¹.*
¹: Dept. of Mechanical and Mechatronics Engineering, University of Waterloo, Canada
* Correspondent author: david.johnson@uwaterloo.ca

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ABSTRACT

Flow over a pitching airfoil is investigated using both PIV and infrared thermography at lower Reynolds number (Re) with application to small wind turbines or aerial vehicles. Airfoil performance in low Re unsteady flow depends not only on the laminar separation bubble (LSB) characteristics (height and length) but also flow characteristics at transition and reattachment points and after that. An SD7037 airfoil with a chord length of 26 mm has been selected to study the whole flow field about the airfoil simultaneously. Because in unsteady motion the flow behavior changes dynamically therefore evaluating the entire airfoil in a single PIV image pair allows the opportunity to obtain a complete understanding of the LSB effects on airfoil performance. This study shows that height of the bubble and following vortices are less than 5-6% of airfoil chord length. Therefore small vibration and surface reflections have significant effects on PIV results. Some parts of these problems are solved by using high pass filtering (HPF) so that boundary layer phenomena are recognizable clearly in instantaneous results. But because of 3D features of unsteady flows, for complete understanding of the phenomena, beside PIV, infrared thermography methods have been used as a second tool in the investigation of the LSB behavior. Infrared thermography results show clear delineation of laminar separation and turbulent reattachment points as a function of angle of attack.

1. Introduction

Predicting the precise aerodynamic behavior of airfoils under varying conditions is one of the ultimate goals of aerodynamics researchers and it will change airfoil design science dramatically. Complex flow over airfoils for aircraft, wind turbines, helicopters, UAV, turbomachinery, etc. create dynamic conditions that challenge current analysis tools. Further understanding will only be possible if there is enough data to investigate flow behavior about different airfoils.

Here, flow over a pitching airfoil is investigated using both PIV and infrared thermography at lower Reynolds number (Re) with application to small wind turbines or aerial vehicles. In this regard, blade design is a crucial part of a small wind turbine. Small wind turbines not only face
low Re flows, but also because of having rotating blades, changes in angle of attack, changes in relative flow velocity and direction, and turbulent flow intensity changes constantly along the blade and unsteady flow conditions develop. All these listed items determine where the laminar flow separates from the surface or if it reattaches to the surface as a turbulent flow along the chord length. In general, for low Re flows, transition occurs with formation of a laminar separation bubble (LSB). Error! Reference source not found. shows a schematic of a LSB and the details of flow behavior around this bubble over the airfoil.

Effects of unsteady motion have been investigated at high Re flows but there are a limited number of studies at low Re flows under unsteady conditions. Lou and Hourtmiadis (2000) studied boundary layer development on a flat plate for a wide range of Re from $1.0 \times 10^5$ to $2.0 \times 10^6$ with a Strouhal number range of 0 to 3. They simulate periodic-unsteady flow by mounting a rotating flap downstream of the test section. Tanaka (2004) studied the quasi-periodic behavior of a LSB at Re=$1.3 \times 10^6$. Following these works, Radespiel et al. (2007) have reported numerical RANS simulations and experimental 2D phase-locked PIV measurements on a SD7003 airfoil model at Re=$6 \times 10^6$. Recent work by Nati et al. (2015) in which they used planar time-resolved PIV to investigate the quantitative characteristics of the LSB over the SD7003 airfoil in a flow with Re=$3 \times 10^6$ while having a pitching oscillatory motion. In addition, tomographic PIV was used for qualitative measurements for the same case study with the frequency ($f$ in equation 1) less than 5 Hz. Regarding the literature review, not enough flow visualization studies have been reported to cover laminar, transition, and turbulent flow under the LSB in low Re flows under unsteady conditions. Therefore performing a complete series of experiments that cover steady
and unsteady flows, and measuring the effect of the LSB on airfoil efficiency can reveal the importance of this phenomenon on the performance of airfoils for wind turbines or UAV’s. In this research, flow behavior around a SD7037 airfoil under unsteady conditions in low Re flow is investigated through flow visualization and by combining the 2D-PIV and infrared thermography (IT) methods.

**IT Background**

Infrared thermography (IT) can be used to measure the boundary layer in both steady and transient cases. Transient cases are in nature much more dynamic and active than steady cases. IT could be applied in dynamic stall cases and to monitor the flow separation on airfoils. All this could be done in a non-intrusive manner with two dimensional imaging Error! Reference source not found.. In flow conditions where the Mach number is much smaller than 1, aerodynamic heating is not sufficient for the IR camera to detect a noticeable temperature difference. In this case, artificial heating could be introduced to increase the temperature difference between the surface and the free stream flow. This could be done either by changing the temperature of the free stream flow, or by changing the surface temperature of the airfoil.

Infrared thermography has typically been used in many ways in qualitative investigations but not for quantitative data. This paper focuses on analyzing infrared images to provide quantitative data about the length and location of separation bubbles. Some of the measurement techniques that have been successfully used to locate the LSB include quantitative oil flow visualization techniques (Ghorbanishohrat and Johnson, 2015), temperature sensitive paints, pressure taps, and PIV. Most recently the location of the LSB was also detected using infrared thermography by Raffel et al. (2015) and Ricci and Montelpare (2005).

**TI and LSB**

At low Reynolds number the flow typically starts off laminar at the leading edge. The laminar boundary layers start to thicken until a sufficient adverse pressure gradient is created that forces the flow to detach. This will cause a temporary instability forcing the flow to reattach to the airfoil and the flow becomes turbulent. This detachment and reattachment causes a separation bubble. The heat flux between the air and the airfoil wall will be different for each of the laminar, turbulent, and separation bubble regions. By measuring the temperature distribution over the surface of the airfoil, it is possible to locate the laminar separation and turbulent reattachment.
At low speeds and adiabatic conditions (where the temperature of the airfoil is similar to air flow around it) the temperature distribution is very small and cannot be detected by an IR camera. To detect the laminar bubble the temperature difference has to be artificially enhanced. There are many different techniques that could be used such as placing heaters on or in the airfoil, or by having infrared heaters heating the pressure side of the airfoil. Heating the airfoil has to be done with care as excessive heating or cooling of the airfoil surface will influence the location of the separation bubble. Constantini et al (2015) showed that the location of the laminar separation is dependent on the pressure gradient on the pressure side and on the temperature difference between the airfoil and the main stream.

In all the experiments mentioned in this paper, the airfoil is oscillating around a mean AOA with a sinusoidal motion. An illustration of this motion, AOA versus time, is shown in Figure 2 AOA sine oscillation with respect to time. Infrared thermography evaluates individual images while differential infrared thermography (DIT) is based on subtracting the captured thermal image from the subsequent image $\alpha_a - \alpha_a$ or $\alpha_b - \alpha_a$.

Astarita et al. (2000) report the distribution of the Stanton number along the suction side of an airfoil. The Stanton number is a measure of heat transfer between the airfoil surface and the mainstream. There are two different Stanton number curves for the laminar and turbulent flow over an airfoil. The Stanton number curve for turbulent flow has a larger magnitude than laminar. The idealized curves are represented in Figure 3. The flow over an airfoil, as mentioned, begins as laminar and follows the laminar curve in Figure 3. After the separation bubble the flow becomes turbulent and the Stanton number moves along the turbulent curve. Figure 3 shows an idealized Stanton number distribution along the chord of the airfoil at different AOA.
Figure 4 also shows the location of the laminar separation (LS) and turbulent reattachment (TR) for each curve. As the AOA increases, the location of the LS and TR move toward the leading edge.

In this experimental study the airfoil was heated so the airfoil is at a higher temperature than the mainstream. This would lead to a temperature distribution inversely proportional to the Stanton number. A higher Stanton number indicating higher heat transfer will lead to lower surface temperatures. The magnitude of the temperature distribution will be greatly influenced by the temperature difference between the airfoil surface and mainstream flow.
In reality the temperature distribution along the chord could be less well defined and with some bias errors making it difficult to extract the location of the LS and the TR. To minimize the bias error and increase the signal to noise ratio the difference between temperature distributions could be determined. Having the differential temperature distribution will produce a clear distinct peak at the separation bubble as shown in Figure 5. Figure 5 shows two separate differential idealized temperature distributions along the chord. During an up-stroke the subsequent AOA is larger so the LS, and TR could be located (refer to Figure 1). In the next differential image LS is located and in the previous differential image TR is located. Therefore, by using DIT the LS and TR could be located for each AOA. During a down-stroke, the subsequent AOA is smaller and in this case, LS and TR are located opposite to upstroke (Raffel et al 2015).

![Figure 5](image)

**Figure 5** Differential temperature distribution along the chord for upstroke and downstroke motion

### 3. Experimental Setup

All the measurements have been performed on a miniature SD7037 airfoil with the chord length of 26 mm. Although using a small model is a very challenging task when working in the vicinity of the surface using PIV or thermography it does allow a high resolution of the local flow. Experiments have been done in a closed circuit subsonic wind tunnel with a test section of 152.4mm×152.4mm×450mm. To adjust the airfoil to a determined angle and simulate the pitching motion, a brushless servo motor (Cleveland Motion Controls MDM-5000) was used. In this servo motor, each degree of rotation represents 22 steps which allows rapid, high precision motion. Further details are available in Gharali and Johnson (2014). A SD7037 airfoil was pitch
oscillated at one quarter of the chord according to the sinusoidal mode (equation Error! Reference source not found.):

\[ \alpha = \alpha_{\text{mean}} + \alpha_{\text{amp}} \sin(2\pi f t) \]  

(1)

where \( \alpha_{\text{mean}} \), \( \alpha_{\text{amp}} \) and \( f \) represent mean angle of attack, pitch oscillation amplitude and oscillation frequency, respectively.

3.1 PIV

In manufacturing the airfoil, aluminum was selected that has a minimum diffuse reflectivity compared with other common materials (Sciacchitano & Scarano 2014). Then it was anodized and painted black to decrease the reflection from the surface as much as possible. A Nd:YAG dual head laser and a Flow Sense EO 4M camera with 60mm f/2.8 Nikkor lens at full 2048px \( \times \) 2048px resolution have been used. Figure 6 shows a schematic of the PIV experiment set up in detail.

![Figure 6 A schematic of PIV experimental setup in detail](image)

3.2 Infrared Thermography

The IR camera used in the experiments mentioned in this paper is a T650sc FLIR camera. The IR resolution is 640 by 480 pixels while the thermal sensitivity is \(<20 \text{ mK} \oplus 30\text{C}. Minimum focus distance is 0.15 m and the image frequency is 30 Hz at full array. The detector type is Focal Plane Array (FPA), uncooled microbolometer with a spectral range between 7.5 and 14 \( \mu \text{m}. \)

Airfoil heating was accomplished by using joule heating through a piece of resistive heating wire on the airfoil pressure side. In order for the wire to have the least amount of effect of the flow around the airfoil a thin heating wire with a diameter of 0.25 mm is chosen. The heating wire is bent in a zig-zag formation to heat the airfoil evenly along its span and chord. A thin layer of Kapton tape is placed between the airfoil and the heating wire because of the conductivity of the
airfoil. Another layer of Kapton tape is placed on top of the heating wire to both attach it to the airfoil and prevent direct thermal contact with air flow. Figure 7 shows the airfoil and the heating wire in addition to the experimental setup.

Figure 7 A schematic of the prepared airfoil pressure surface (top) and infrared thermography experimental setup

In these experiments, Re = 3.8×10^4 with unsteady motion via sinusoidal oscillation about the quarter chord of the airfoil as given in equation Error! Reference source not found..

\[ \alpha = 11° + 11°\sin(2\pi ft) \quad (2) \]

Most of the complex phenomena in unsteady motion which are related to dynamic stall occur after the static stall angle of attack which is about 11° for the SD7037 at this Re. Therefore, selecting \( \alpha_{\text{mean}} \) close to the static separation AOA can reveal useful information of flow behavior in unsteady motion; the physical frequencies are 15 and 25 Hz (\( k=\pi fc/u=0.05, 0.08 \) correspondingly).

4. Results and discussion

For the PIV method, after acquiring images, the next step is image post processing. In general, the velocity field can be calculated from the PIV images. But, in this experiment the desired area is a very small layer in the vicinity of the airfoil surface considering that the chord of the airfoil is 26 mm and field of view adjusted to be about 29mm×29mm. Due to laser light reflection in this narrow area there is significant noise that can change the PIV correlation peaks. Based on recent
research (Sciachitano & Scarano 2014) it is possible to separate these excess light contributions by analyzing the images in the frequency domain. After some study, a high-pass filter (HPF) with a 3x3 kernel was used in this research as an image filter to make edges of the structures more recognizable (Dantec Dynamics A/S 2013), Error! Reference source not found.

Figure 8 A sample of images: original image (above) in addition to the post processed result, (U component velocity contour) and filtered one by HPF 3x3 (bottom).

One of the advantages of using a small airfoil is that only by using one camera, the entire flow field can be studied that saves time, and decreases the uncertainty of combining the images. To estimate the dimension of the LSB over the airfoil, Figure 9 shows the grid mesh of 64×64 and 8×8 on a picture of the airfoil at a sinusoidal motion with an AOA of 9 degrees. In this figure a color map has been used to clarify the shape and dimensions of the LSB in addition to the following generated vortices. These pictures clearly show that the first vortex has a 1.5 mm diameter and that the height of the LSB is about 1-2mm which is about 5% to 6% of chord length.
Therefore, what is obvious here is that the boundary layer is extremely close to the surface. To show the accuracy of the obtained results for the airfoil with the chord and field of view length of 26 mm and 29 mm, correspondingly, Figure 10 shows the original images with velocity covariance contours for AOAs of 9° to 14° and k=0.05. The effect of increasing the AOA is accompanied by the shortening of the LSB until 14°. In this condition, the LSB has broken down to the Leading Edge Vortex (LEV) which can be one of the signs of nearing the occurrence of the dynamic stall process. The LEV changes the effective shape of the LE and it influences the flow towards dynamic stall (Gharali & Johnson 2013). The location of the laminar-turbulent transition point is obtained by considering a critical number of 0.001(Ol et al. 2005) for the normalized Reynolds shear stress and shows that the unsteady transition point moves towards the LE with increases in the AOA that is in agreement with previous work.

Figure 9 Airfoil model in 9 deg. unsteady motion: a) original image with grayscale, (b) color map, (c) 64x64 mesh size and (d) 8x8 mesh size
Figure 10 PIV images at different angles of attack (9, 11, and 14 deg) at f=15Hz with their velocity covariance contour (right).

Figure 11 shows 6 random sample images of 800 PIV images in sinusoidal motion at a predetermined specific AOA. As can be seen the separation point is almost constant and recognizable by eye as well as the height of the bubble. But the ‘vortex roll up location’ (Nati et al. 2015) and reattachment point are less obvious.
Figure 11 Random PIV images of determined AOA during Pitch oscillation

Figure 12 shows the velocity vectors and streamlines for an instantaneous and average of 400-800 images. As can be seen, because of small dimensions in these experiments even a little change in structure and location of vortices can cause uncorrected average results on the average size and location of vorticities and the height of the bubble subsequently. Averaging of multiple PIV results is not representative of the flow field particularly after the bubble. Until now, the problem of reflection and somehow the vibration of the airfoil, considering even 0.1mm movement in the y direction can be significant. These issues have been solved but still work on the convergence of the data continues.

Figure 13 shows results from three different angles of attack during pitching motion. As can be seen, the length and height of the bubbles change significantly with small changes in angle of attack. But also by comparing two angles of 12° and 13°, it is clear that the flow field after the bubble is different due to the shape and location of vortices that causes different turbulent flow characteristics. It is clear that it is important to have more information about turbulent flow structure after the bubble. Detailed study of the turbulent flow characteristics gives more
information about the effects of the bubble on airfoil performance. For the dynamically pitching airfoil the rate of increasing lift and drag from 13° to 14° is higher than from 12° to 13° as shown in Gharali and Johnson (2013, 2014). Therefore, for full understanding of LSB effects over the airfoil, studying of turbulent flow features after the bubble is necessary.

One solution is using an easier and faster method along with 2D PIV to evaluate the flow behavior over the airfoil in 3D. In this research, the possibility of using the IT or DIT method has been explored. Then using a technique such as infrared thermography to evaluate the entire span can help to recognize the transition and reattachment points. Also, it may help to find the periodic behavior of the breaking vortices after the bubble. In this case, the relation of the lift with vortex circulation along with position and size of vortices may be investigated.
Thermal results
After taking the thermal images at different AOA, the temperature distribution is plotted against the chord. The temperature shown in Figure 14 is the average temperature across the span of the airfoil at each x/c value. The temperature trend line is very similar to that in Figure 4. The LS is located at the first peak in the temperature profile. The TR is located at the base after the first peak. The temperature distribution for different AOA predict that the bubble size decreases and moves toward the leading edge.

![Figure 14 Span wise average temperature distribution along the chord for different AOA (static AOA cases)](image)

The following Figure 15 shows the location of the LS and TR extracted from the temperature distribution along the chord (Figure 14). The linear relation for LS or TR is expected and has also been found using different techniques such as surface oil visualization (Ghorbanishohrat and Johnson, 2015).
5. Conclusion

The goal of this research is study of low Re flow behavior over a SD7037 airfoil in steady and unsteady conditions by using PIV, IT and DIT. Airfoil performance in low Re unsteady flow depends not only on the LSB characteristics (height and length) but also flow characteristics at transition and reattachment points and after that. In this research, the airfoil with a chord length of 26 mm has been selected to study the whole flow field about the airfoil simultaneously. Because in unsteady motion the flow behavior changes dynamically therefore evaluating the entire airfoil allows the opportunity to obtained a complete understanding of the LSB effects on airfoil performance. This study shows that height of the bubble and following vortices are less than 5-6% of airfoil chord length. Therefore small vibration and surface reflections have significant effects on PIV results. Some parts of these problems are solved by using HPF so that boundary layer phenomena are recognizable clearly at instantaneous results. But because of 3D features of unsteady flows, for complete understanding of the phenomena, beside PIV, infrared thermography methods have been used in the span wise direction.

6. References


Gharali, K. & Johnson, D., 2013. Reduced frequency effects on Laminar Separation Bubbles. 10th International Symposium on Particle Image Velocimetry, Delft, NL.


