An Experimental Study on Active Flow Control Using Synthetic Jet Actuators over S809 Airfoil

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Abstract. This study investigates the effect of periodic excitation from individually controlled synthetic jet actuators on the dynamics of the flow within the separation and re-attachment regions of the boundary layer over the suction surface of a 2D model wing that has S809 airfoil profile. Experiments are performed in METUWIND’s C3 open-loop suction type wind tunnel that has a 1 m x 1 m cross-section test section. The synthetic jet array on the wing consists of three individually controlled actuators driven by piezoelectric diaphragms located at 28% chord location near the mid-span of the wing. In the first part of the study, surface pressure, Constant Temperature Anemometry (CTA) and Particle Image Velocimetry (PIV) measurements are performed over the suction surface of the airfoil to determine the size and characteristics of the separated shear layer and the re-attachment region, i.e. the laminar separation bubble, at 2.3x10^5 Reynolds number at zero angle of attack and with no flow control as a baseline case. For the controlled case, CTA measurements are carried out under the same inlet conditions at various streamwise locations along the suction surface of the airfoil to investigate the effect of the synthetic jet on the boundary layer properties. During the controlled case experiments, the synthetic jet actuators are driven with a sinusoidal frequency of 1.45 kHz and 300Vp-p. Results of this study show that periodic excitation from the synthetic jet actuators eliminates the laminar separation bubble formed over the suction surface of the airfoil at 2.3x10^5 Reynolds number at zero angle of attack.

1. Introduction
Controlling loads on a wind turbine rotor is an important issue because not only a higher rotor performance can be achieved but also a decrease in fatigue loads is also potentially possible [1]. Early commercial wind turbines were stall regulated. In stall regulation control, blade pitch is fixed and turbine rotational speed is near constant. As the turbine rotor size has increased over the years, collective pitch control with variable speed rotors have been developed and today most large wind turbines utilize this method for turbine control. Pitching causes the blades to rotate around their spanwise axis in order to alter the inflow angle as a response to the changes in the wind. However, this method is generally slow to respond to changes in the wind speed and it is not capable of handling loads caused by rotor yaw errors, wind shear, wind gusts, shaft tilt, wind upflow and turbulence [2]. Therefore, new advanced flow control methods for load alleviation are being investigated by various research groups. Some examples of these methods are advanced pitch control which includes cyclic and individual pitch control concepts (e.g., Bossanyi et al., 2000 [3], 2004 [4]; Larsen et al., 2005 [5]), adaptive trailing edge geometry (e.g, Basualdo, 2005 [6]), microtaps (e.g, Mayda, van Dam, and
Yen-Nakafuji, 2005 [7]), plasma actuators (e.g., Nelson and Corke, 2008 [8]) and synthetic jet actuators (e.g., Stalnov et al., 2010 [9]; Maldonado et al., 2009 [10]).

Another issue is related to the performance and efficiency of small wind turbines, the blades of which usually have to operate at low Reynolds numbers. It is known that at low Reynolds numbers between $10^4-10^5$ range, laminar boundary layer tends to separate and mostly re-attach at low angles of attack forming a laminar separation bubble. If the angle of attack is high enough complete separation will occur without re-attachment. For small wind turbines, the aerodynamic performance of the airfoil sharply decreases and a wide or narrow wake region can be formed depending on the characteristics of the separation on the airfoil. For small wind turbine blades, separation is the primary cause of poor aerodynamic performance and therefore the low turbine efficiency. On the other hand, even at reasonably high Reynolds numbers such as $3 \times 10^5$ and at zero angle of attack a laminar separation bubble can still be observed such as the one on the suction surface of S809 airfoil as reported in Somers [11].

A potential active flow control device for preventing separation is synthetic jet actuators. A synthetic jet actuator is a device that generates a synthesized jet from the ambient fluid through an orifice or slot due to the oscillation of a diaphragm placed on one (or more) of the walls of a sealed cavity. Synthetic jet actuators typically consist of a sealed cavity, an orifice or slot and a diaphragm (an oscillating material). Piezoelectrically driven diaphragms (e.g., Smith and Glezer, 2005 [13]; Hong, 2006 [12]) electromagnetically driven pistons (e.g., Schaeffler and Jenkins, 2006 [14]) and diaphragms driven by an acoustic source (e.g., Milanovic and Zaman, 2005 [15]) are common drivers for the diaphragm of a synthetic jet actuator. A very significant feature of synthetic jets is that they form from the working fluid of the system and therefore they add linear momentum to the system without any mass addition. That is why they are called zero net mass flux actuators. In addition, due to this zero net mass nature no external plumbing is needed which is one of the advantages of synthetic jet actuators.

There are many studies demonstrating the effectiveness of synthetic jet actuators on separation control (e.g., McCormick, 2000 [16]; Amitay et al., 2001 [17]; Tuck and Soria, 2004 [18]). However, there are few studies investigating the effectiveness of synthetic jet actuators on wind turbine applications. Recently, Stalnov et al. (2009) [9] and Maldonado et al. (2009) [10] studied the effectiveness of synthetic jet actuators on the airfoil performance. Stalnov et al. (2009) performed experimental studies using synthetic jet actuators over a two dimensional IAI pr8-SE airfoil, a thick airfoil suitable for wind turbine rotor blades. They investigated the effect of the actuators on the performance of the airfoil by controlling the boundary layer separation and they compared the results with the ones they obtained using mechanical vortex generators (VG). Based on their experiments, they demonstrated that synthetic jet actuators are effective for a wide range of Reynolds number while VGs perform well only at design Reynolds number. In addition, they stated that since synthetic jet actuators are effective in low Reynolds numbers, they can be used to reduce the cut-in speed of wind turbines which as a result will increase the maximum lift of the airfoil at low Reynolds numbers. Maldonado et al. (2009) conducted several experiments using an array of synthetic jet actuators over a small scale S809 finite wind turbine blade. They investigated the effect of the actuators on the blade’s structural vibration by controlling the boundary layer separation at a range of Reynolds number between $7.1 \times 10^4$ and $2.38 \times 10^5$, and post stall angles of attacks from 15 to 17.5 degrees. They found that there is a relation between the degree of the flow separation and the reduction in the blade’s structural vibration. In this study, an array of synthetic jet actuators driven by piezoelectric materials is placed over the suction surface of a wing model that has a S809 airfoil profile. This study aims to investigate the effect of synthetic jet actuators on the separated shear layer over the suction surface of the S809 airfoil at Reynolds number of $2.3 \times 10^5$ at zero angle of attack. In addition, this study provides baseline information about the dynamics of the flow and its development within the shear layer over S809 airfoil profile at $2.3 \times 10^5$ Reynolds number at zero angle of attack.
2. Experimental Setup and Methodology
Experiments are conducted in METUWIND’s C3 open-loop suction type wind tunnel. The wind tunnel has a 2D contraction section with an area ratio of 1:5 and a fully transparent test section with a cross sectional area of 1x1 m² and a length of 2 m. The tunnel is powered by a 45 kW speed-controlled electrical motor that drives a 1.2 m diameter axial fan. Inlet guide vanes at the entrance of the contraction, a honeycomb and a screen are put upstream of the test section to maintain appropriate flow quality. Speeds up to about 25 m/s are attainable within the test section and the average free stream turbulence intensity of the tunnel is 0.5%.

![Figure 1. Picture of METUWIND’s suction type wind tunnel that has a 1 m x 1 m test section area.](image1)

The wing model used in the experiments has a S809 airfoil profile. The wing span and the chord are 0.99 m and 0.455 m, respectively. On the suction side of the wing, a 0.536 m long spanwise part is detachable and there are three different configurations of this detachable part. These detachable parts are designed for baseline and controlled case measurements.

![Figure 2. Compact view of the S809 blade for the baseline case study (a), detachable part with the synthetic jet actuators for the controlled case study (b), detachable part with pressure taps (c), exploded (d) and compact (e) view of the synthetic jet actuators.](image2)

Three individually controlled synthetic jet actuators are located at 28% chord location near the middle of the span. Each synthetic jet has a rectangular orifice with a width of 0.5 mm and a length of 10 mm...
and is spaced 27.37 mm apart. Each synthetic jet is driven by a Thunder 5C piezoelectric actuator, manufactured by Face International Cooperation, with a sinusoidal actuation of 1450 Hz and 300Vpp. For the surface pressure measurements, the mid span of the blade is instrumented with 31 pressure taps placed in the chordwise direction, and the taps are connected to ESP Pressure Scanner. The scanner has 32 channels with 0.03% accuracy.

CTA and PIV measurements are performed at 3.25 cm away from the mid span plane of the blade. CTA measurements are conducted with a Dantec type single wire normal probe at several chordwise locations. At each chord location, the hot wire sensor is traversed along the boundary layer thickness to obtain boundary layer properties. The probe is attached to a holder mounted on a remotely controlled traversing mechanism with an accuracy of 0.076 mm. The sample rate of the hot wire is 5 kHz and the sample size of each realization is 10000.

For the 2D PIV measurements, a TSI Particle Image Velocimetry system, which consists of a 30 mJ/pulse Nd:YLF high-speed laser and a 12-bit high-speed Phantom camera is used. During the measurements a 105 mm Macro Sigma lens is used along with a 20 mm extension tube in order to increase the magnification, and the camera is operated at 742 Hz with 4 megapixel resolution. For each measurement window, 285 image pairs are obtained and ensemble-averaged to obtain the average vector field. During the data processing, TSI Insight 4G software is utilized in order to obtain the vector maps for each window. An adaptive algorithm starting from 64x64 pixels interrogation area size and decreasing down to 32x32 pixels is applied to the raw data with 50% interrogation area overlap along with the post-processing algorithms of vector validation and vector conditioning.

3. Results

Baseline Measurements

Surface pressure measurements are conducted to provide an insight into the boundary layer development over the suction surface of the airfoil. Upper surface pressure distribution for 2.3x10^5 Reynolds number and at zero angle of attack is presented in Figure 3, together with OSU data [19] and inviscid flow solution obtained using XFOIL.

![Figure 3. Upper surface pressure distribution](image)

From a comparison of the experimental data at 2.3x10^5 Reynolds number and the inviscid flow pressure distributions, it is seen that there is a significant decrease in the suction peak which is typical for airfoils operating at low Reynolds numbers. The constant pressure region and the sudden recovery of pressure in the pressure distribution indicate that a separation bubble forms over the suction surface
of the airfoil. The constant pressure region is an indication of separation and the sudden pressure recovery demonstrates the presence of transition. As proposed by Tani [20] the reattachment location for small separation bubble can be predicted as the location where the pressure value is the same for both separated flow and inviscid flow. A comparison between the current experimental data and the OSU data shows that although the separation location seems to be close for these two Reynolds numbers, transition and reattachment occurs further downstream for the lower Reynolds number case as expected.

Particle Image Velocimetry (PIV) measurements are carried out to resolve the size and characteristics of the separation over the suction surface of the airfoil for the baseline case. Figure 4 demonstrates the velocity magnitude and Reynolds shear stress distribution per unit mass within and outside the laminar separation bubble, and Figure 5 presents the boundary layer profiles of mean streamwise velocity (U) normalized by local edge velocity (Ue) at 2.3x10^5 Reynolds number and zero angle of attack. Reynolds stress per unit mass is calculated using the following equation:

\[-\bar{u}' \bar{u}' = \frac{1}{N} \sum_{k=1}^{N} [(u_i)_k - \bar{u}_i] [(u_j)_k - \bar{u}_j]\] (1)

where, \(u'\) and \(\bar{u}\) represent the fluctuating and mean velocities, respectively.

In Figure 4(a), a dead air region and a strong recirculation zone around 60.8% chord location is clearly visible within the laminar separation bubble. Since a rapid increase in Reynolds shear stress is an indication of transition onset, based on the Figure 4(b), it is observed that transition begins around 59.5% chord location. From Figure 5, it is seen that the laminar boundary layer separates around 48.1% chord location and it reattaches to the wall around 65% chord station.
Figure 4. Velocity magnitude (a) and Reynolds shear stress distributions per unit mass (b)
Figure 5. Boundary layer profiles of mean streamwise velocity normalized by local edge velocity obtained from PIV measurements.
Figure 6 compares boundary layer profiles of mean streamwise velocity normalized by local edge velocity obtained from CTA and PIV measurements at three different chord stations. From this figure, it is seen that PIV and CTA results are consistent with each other.

**Figure 6.** Comparison of boundary layer profiles of mean streamwise velocity normalized by local edge velocity obtained from CTA and PIV measurements at three different chord stations.

**Measurements with Synthetic Jet Actuation**

Single wire constant temperature anemometry measurements with and without synthetic jet actuators are conducted at various chordwise location to determine the effect of the actuation on the laminar separation bubble. Figure 7 and Figure 8 show the mean and fluctuating velocity profiles at the traversed chordwise locations, respectively. The mean and the fluctuation velocities are normalized by the local edge velocity of the boundary layer. Similarly, wall normal distance is normalized by the local chord length. According to Figure 7, it is seen that for the baseline case, there is no inflection point visible in the mean velocity profiles at 43.3% chord station. Also, fluctuating velocities are low. Thus, the flow has not separated yet. At 48.1% chord station, on the other hand, although an inflection point is not clearly visible in the mean velocity profile, fluctuating velocity level is much higher than the previous measurement station 43.3% chord. This rapid increase in the fluctuating velocity level may be an indication of laminar boundary layer separation near this location. This result support the separation point obtained from PIV measurements. After the separation point, fluctuating velocity levels increase both in the streamwise and normal direction as observed in Figure 8. However, near the wall there is a region with near zero mean and fluctuating velocity, which indicates a dead air region where the flow is almost stationary. 51.2% and 58.2% chord locations seem to be inside or very close to this dead air region. Downstream the dead air region, both the mean and fluctuating velocities increase again near the wall. This may be due to a strong recirculation region which is known to cause a strong momentum exchange between the free stream and the flow within the separated shear layer, and therefore, to cause the separated shear layer to reattach to the surface again. Burgmann and Schröder (2008) [21] state that due to the disturbances within the boundary layer, shear layer rolls up downstream and this process, at the rear of the separation bubble, generates vortices which causes fluid transformation towards the wall and away from the wall on the downstream and on the upstream of the vortex, respectively. Downstream the 65% chord location, it is observed that the peaks in the fluctuating velocity profiles disappear, and fluctuating velocities are almost constant near the wall. This indicates that the flow reattaches to the airfoil surface near 65% chord location, forming a laminar separation bubble. After reattachment it is seen that flow develops downstream with fuller
mean velocity profiles near wall which is a typical behaviour of turbulent boundary layer flows. All these results obtained from hot wire measurements agree with PIV data.

**Figure 7.** Boundary layer profiles of mean streamwise velocity normalized by local edge velocity obtained from CTA measurements at different chord stations.

With the synthetic jet actuators on, it is seen in Figure 7 that the inflection points in the mean velocity profiles of the baseline case have disappeared. In addition, from the fluctuating velocity profiles in Figure 8, no peak fluctuation is detected within the shear layer away from the wall. This also proves the absence of inflection points in the boundary layer. Furthermore, the dead air region, strong
recirculation zone, and therefore, the laminar separation bubble, is detected to be eliminated by the periodic excitation from the synthetic jet actuators.

**Figure 8.** Boundary layer profiles of streamwise fluctuation velocity normalized by local edge velocity obtained from CTA measurements at different chord stations.

Figure 9 compares the wake profile at 4 mm (about 1% chord) downstream the trailing edge when the synthetic jet is switched on and off. In the wake profile, the local mean velocities are normalized by the mean freestream velocity ($U_0$), and the traversed distance ($y$) along the wake thickness is normalized by the chord ($c$) of the blade. As seen in Figure 9, the wake profile is diminished on the
suction side due to the effect of the synthetic jet. On the pressure side, however, the effect of the actuation is not significant since the actuation is presented on the suction side only and the measurement location is very close to the blade trailing edge. Based on the momentum method, the profile drag coefficient of the controlled airfoil is found to be approximately 19.6% less than the baseline case. However, it should be noted that for more accurate profile drag determination, measurement should be carried out at further downstream of the trailing edge where the static pressure has returned to upstream tunnel static pressure and at several spanwise locations.

The effect of synthetic jet on the boundary layer integral quantities is also investigated. According to Hatman and Wang [22], the maximum value of the displacement thickness in laminar separation is an indication of the transition onset. Thus, maximum value of the displacement thickness in Figure 10 demonstrates that transition begins around 60% chord location. In Figure 11, the shape factors for the baseline case and the controlled case are compared. For the baseline case, it is seen that the shape factor is first increasing and then decreasing significantly. This significant increase in the shape factor indicates that flow separation occurs, and at the location where the rapid decrease in the shape factor ends the separated flow reattaches to the surface. For the baseline case it is detected that flow separation and reattachment occurs around 48.1% and 65% chord stations, respectively. For the controlled case study, on the other hand, a significant increase in the shape factor is not detected in Figure 11.

**Figure 9.** Mean velocity profile at 4 mm downstream the trailing edge, at $2.3 \times 10^5$ Reynolds number and at zero angle of attack.

**Figure 10.** Displacement and momentum thickness values for baseline case (obtained from CTA measurements) at different chord locations.

**Figure 11.** Effect of synthetic jet on the shape factor (obtained from CTA measurements) at different chord locations.
4. Conclusion
In this study, first of all, the dynamics of the flow within the laminar boundary layer over the suction surface of the S809 airfoil profile is investigated at Reynolds number of 2.3x10^5, at zero angle of attack. For the baseline case, surface pressure, PIV and CTA measurements demonstrate that a laminar separation bubble exists over the suction surface of the airfoil and it covers a region of 19.6% chord distance. In the second part of the study, an array of synthetic jet actuators is flush mounted over the suction surface of the blade near the mid span, and the effect of the periodic excitation from the actuators on the laminar separation bubble and other boundary layer quantities are investigated with CTA measurements. Results show that synthetic jet from the actuators eliminates the laminar separation bubble. However, further research is required to be conducted to see the effect of these devices on lift and drag performance of such airfoils operating at low Reynolds numbers at different angles of attack.

5. References
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