7. ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2013 085**

11-13 September 2013 - METU, Ankara TURKEY

AN EXPERIMENTAL STUDY ON ACTIVE FLOW CONTROL OVER S809 AIRFOIL USING SYNTHETIC JET ACTUATORS

Melika GÜL[1], Oğuz UZOL[2], and İ. Sinan AKMANDOR[3]

Department of Aerospace Engineering, Middle East Technical University (METU)

Middle East Technical University, METU Center for Wind Energy (METUWind)

06800 Ankara, Turkey

ABSTRACT

This paper presents an experimental investigation of the effect of an array of synthetic jets on the separated shear layer of a model wing that has a S809 airfoil profile. Hot wire measurements are performed at 2.3×10^5 Reynolds number with and without synthetic jet actuation. The array consists of three individually controlled synthetic jet actuators driven by piezoelectric diaphragms located at 28% chord location near the middle of the span. In the first part of the study, measurements are conducted without synthetic jet actuators as a baseline case at Reynolds number of 2.3×10^5 at zero angle of attack. The objective is to resolve the size and characteristics of the separated shear layer. Afterwards, the effect of the synthetic jet actuators on the flow characteristics is investigated. The results of the study prove the effectiveness of synthetic jet actuators on flow control.

INTRODUCTION

First commercial wind turbines were stall regulated. In stall regulation control, the blade pitch is fixed and the turbines rotational speed is near constant. Although stall control of wind turbine blades is very simple, this method is uneconomical for large rotor blades (Barlas and Kuik, 2010). As the rotor size has increased over the years, collective pitch control with variable speed rotors have been developed. Today most of large wind turbines utilizes this 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 slow to respond to changes in the wind speed and it is not capable of handling the loads caused by rotor yaw errors, wind shear, wind gusts, shaft tilt, wind upflow and turbulence (Berg et al., 2007). 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 (e.g., Bossanyi et al., 2000, 2004; Larsen et al., 2005), adaptive trailing edge geometry (e.g, Basualdo, 2005), microtaps (e.g, Mayda, van Dam, and Yen-Nakafuji, 2005), plasma actuators (e.g., Nelson and Corke, 2008) and synthetic jet actuators (e.g., Stalnov et al., 2010; Maldonado et al., 2009).

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; Hong, 2006) electromagnetically driven pistons (e.g., Schaeffler and Jenkins, 2006) and diaphragms driven by an acoustic source(e.g., Milanovic and Zaman, 2005) 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; Amitay et al., 2001; Tuck and Soria, 2004). However, there are few studies investigating the effectiveness of synthatic jet actuators on wind turbine airfoils. Recently, Stalnov et al. (2009) and Maldonado et al. (2009) 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 synthetic jet actıators 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 7.1×10^1 and 2.38×10^2, 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 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 of the wing model at Reynolds number of $2.3x10^5$ at zero angle of attack. In addition, this study provides information about the interaction of synthetic jet with boundary layer under adverse pressure gradient, which is not well understood and documented in the literature.

METHODOLOGY

Experiments were conducted in METUWIND's low speed suction type wind tunnel. This wind tunnel includes a 2D contraction section with an area ratio of 1:5, a fully transparent test section with a cross sectional area of 1x1 m2 and a length of 2 m,and it's 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 installed upstream of the test section to maintain appropriate flow quality. Speeds up to about 24 m/s are attainable within the test section and the average free stream turbulence intensity of the tunnel is 2.25 %.

Figure1. Picture of METUWIND's suction type wind tunnel that has a 1 m x 1 m test section area.

Wing Model

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. The first configuration is designed for surface pressure measurements and manufactured from plexiglass with 31 pressure taps at the mid span in the chordwise direction. The pressure taps are 1 mm diameter and normal to the surface of the wing with an l/d ratio of 2.5, where l is the length and d is the diameter of the hole. The second and third detachable parts are designed for baseline and controlled cases and are made up of ABS plastic. The wing model and the detachable parts are shown in Figures 2 and 3, respectively.

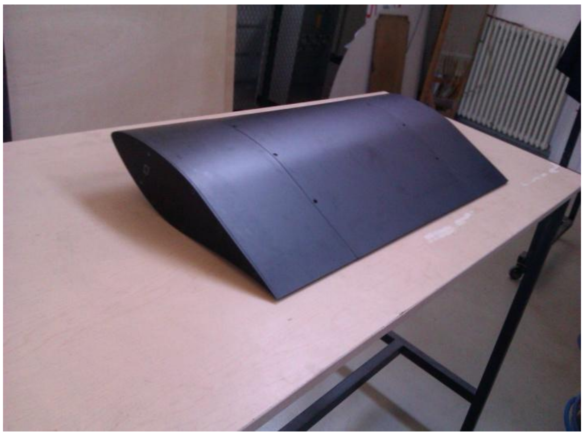

Figure 2. S809 blade for the baseline case

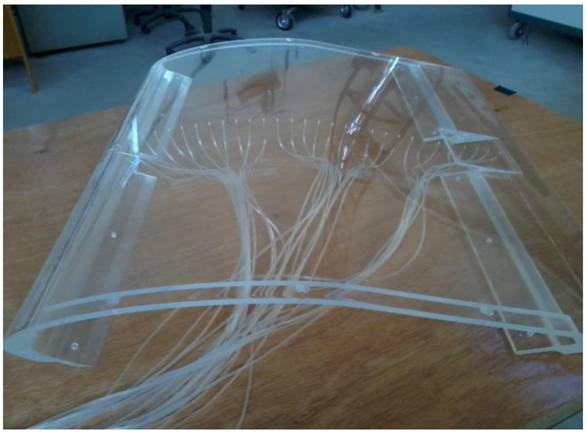

Figure 3. Detachable part with pressure taps

Synthetic Jet Actuators (SJA)

Three individually controlled synthetic jet actuators were located at 28% chord location in 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 are spaced 27.37 mm apart. Each synthetic jet was driven by Thunder 5C piezoelectric actuator, manufactured by Face International Cooperation, with a sinusoidal actuation of 1450 Hz.

Figure 4.Thunder actuator TH-5C [Face Inc.].

RESULTS

Characteristics of the Synthetic Jet Actuators

Synthetic jet actuators were characterized over a frequency range from 50Hz to 2200Hz under quiescent flow in order to check for any first or second harmonic peaks and also decide the operating frequency of the actuators. Figure 5 shows the variation of the mean velocity with various forcing frequency without cross flow. Velocity was measured using constant temperature anemometry at a position y/d=2 along the centerline of the orifice of the synthetic jet actuator, where d is the width of the orifice.

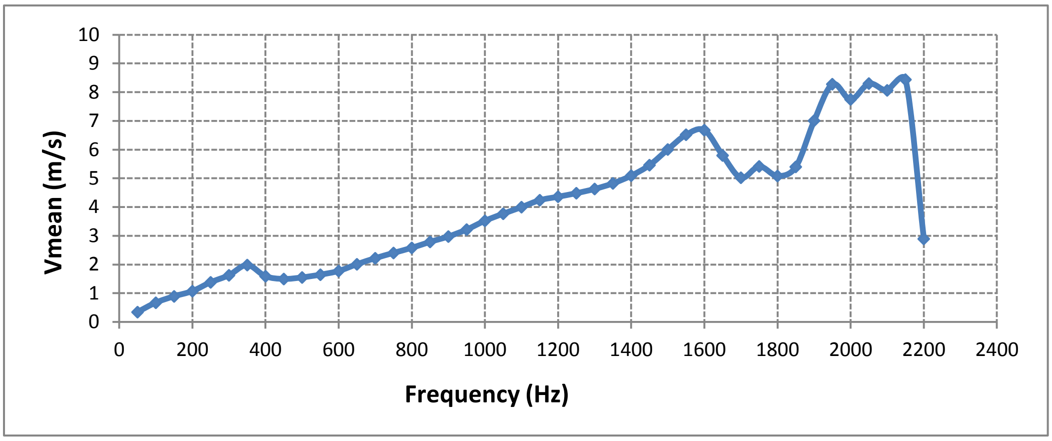

Figure 5. Mean velocity at various forcing frequency at y/d = 2 with no cross flow. Forcing amplitude = 300Vp-p

Figure 5 shows that the maximum mean velocities occur around 1950Hz -2150 Hz, which may be attributed to the coupling between acoustic frequency of the cavity and the resonant frequency of the Thunder 5C piezoelectric material. Also, in the figure it is seen that when the actuator is driven with 1450 Hz, it generates a moderate mean velocity which is considered as high enough to control the flow over the airfoil and low enough not to trigger the disturbances further. Therefore, 1450 Hz was determined to be the driving frequency of the actuators.

Surface Pressure Measurements

Mid-span surface pressure measurements were performed over the suction surface of the S809 blade at 2.3×10^5 Reynolds numbers at zero angle of attack.

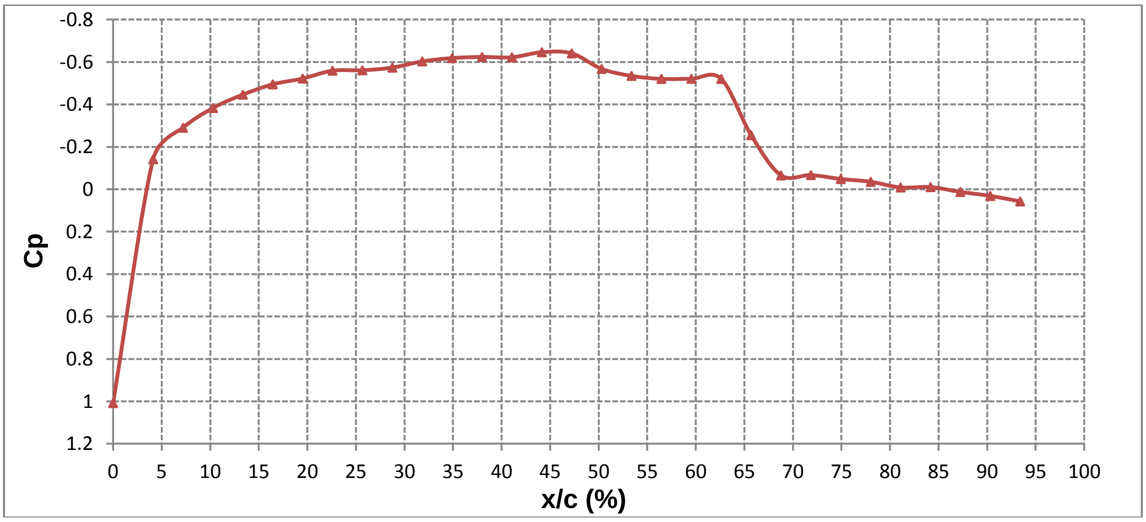

Figure 6. Surface Cp distribution.

In the Figure 6, it is clearly seen that at this Reynolds number boundary layer separates before 55% chord station, and after separation a constant pressure region appears in the pressure distribution curve. At the aft portion of the blade, flow reattachment occurs around 70% chord location. The constant pressure region formed on the pressure distribution curve shows that a separation bubble forms over the suction surface of the airfoil. This behaviour is a typical character of an airfoil operating at low Reynolds numbers when separation occurs.

Effect of Synthetic Jet Actuators on Boundary Layer

In order to determine the effect of the synthetic jets on the flow development within the separated boundary layer, hot wire measurements (CTA) were conducted at several locations near the mid span of the blade along the chordwise direction with and without synthetic jet actuators on. At each traverse station hot wire was traversed along the local boundary layer thickness in order to determine the boundary layer profiles. Following figures, Figure 7 and Figure 8, demonstrate the mean and the fluctuating velocity profiles, respectively, within the boundary layer at several chord locations near the mid span at 2.3×10^5 Reynolds number at zero angle of attack. The mean and fluctuation velocities are normalized by local edge velocity of the boundary layer. Similarly, wall normal distance is normalized by the local chord distance.

The fluctuating velocity was calculated from the below formula

$$u' = \sqrt{\frac{\left(\sum_{i=1}^{N}(U_i - \bar{U})\right)}{N}}$$

During the controlled case experiments, synthetic jet actuators were driven by a sinusoidal forcing frequency that was generated by a function generator. The forcing amplitute is the peak to peak amplitude of the sine wave.

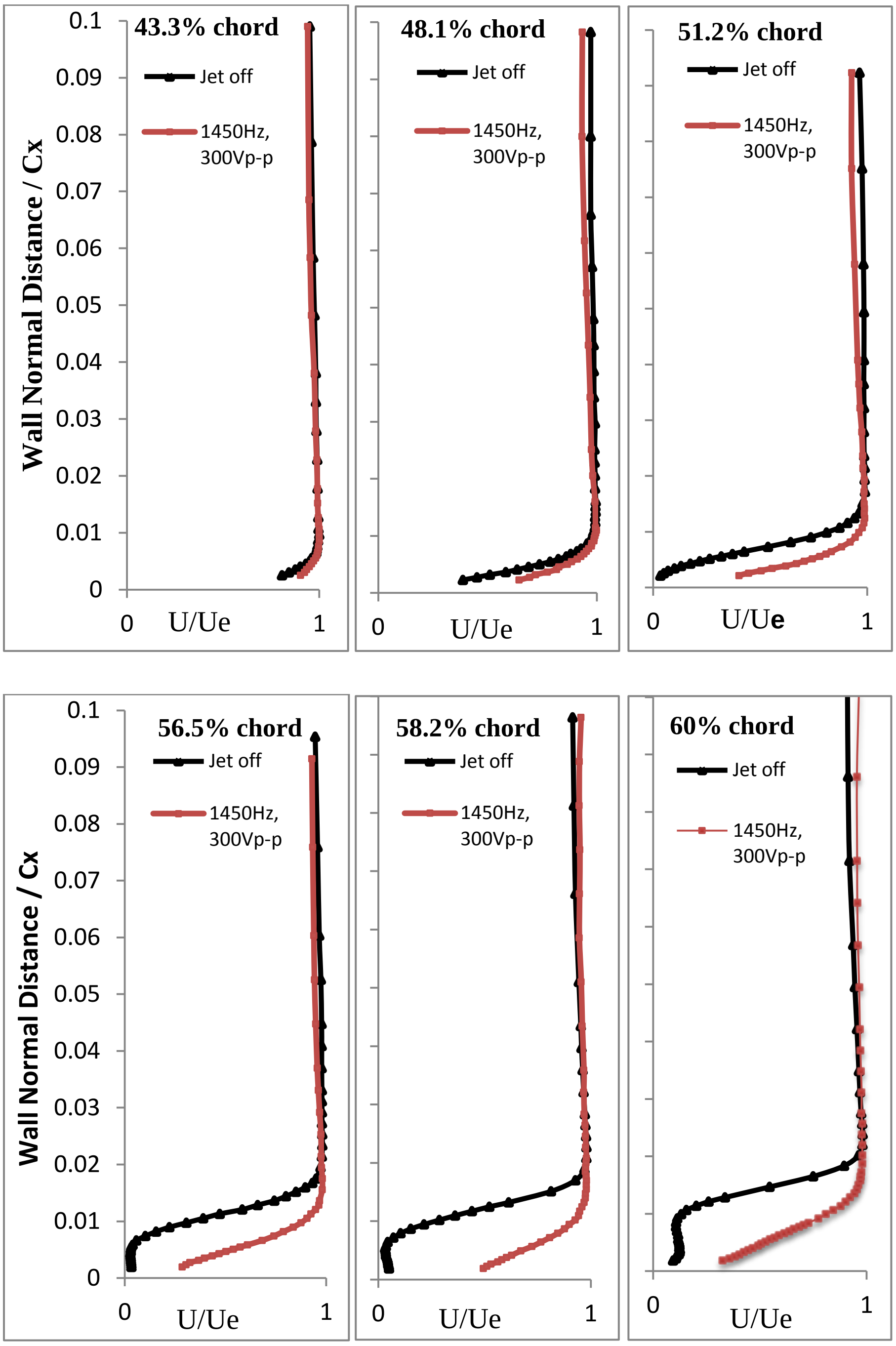

Figure 7.Comparison of the mean velocity profiles with the SJA switched on and off. Forcing amplitude is 300Vp-p and forcing frequency is 1450Hz.

.

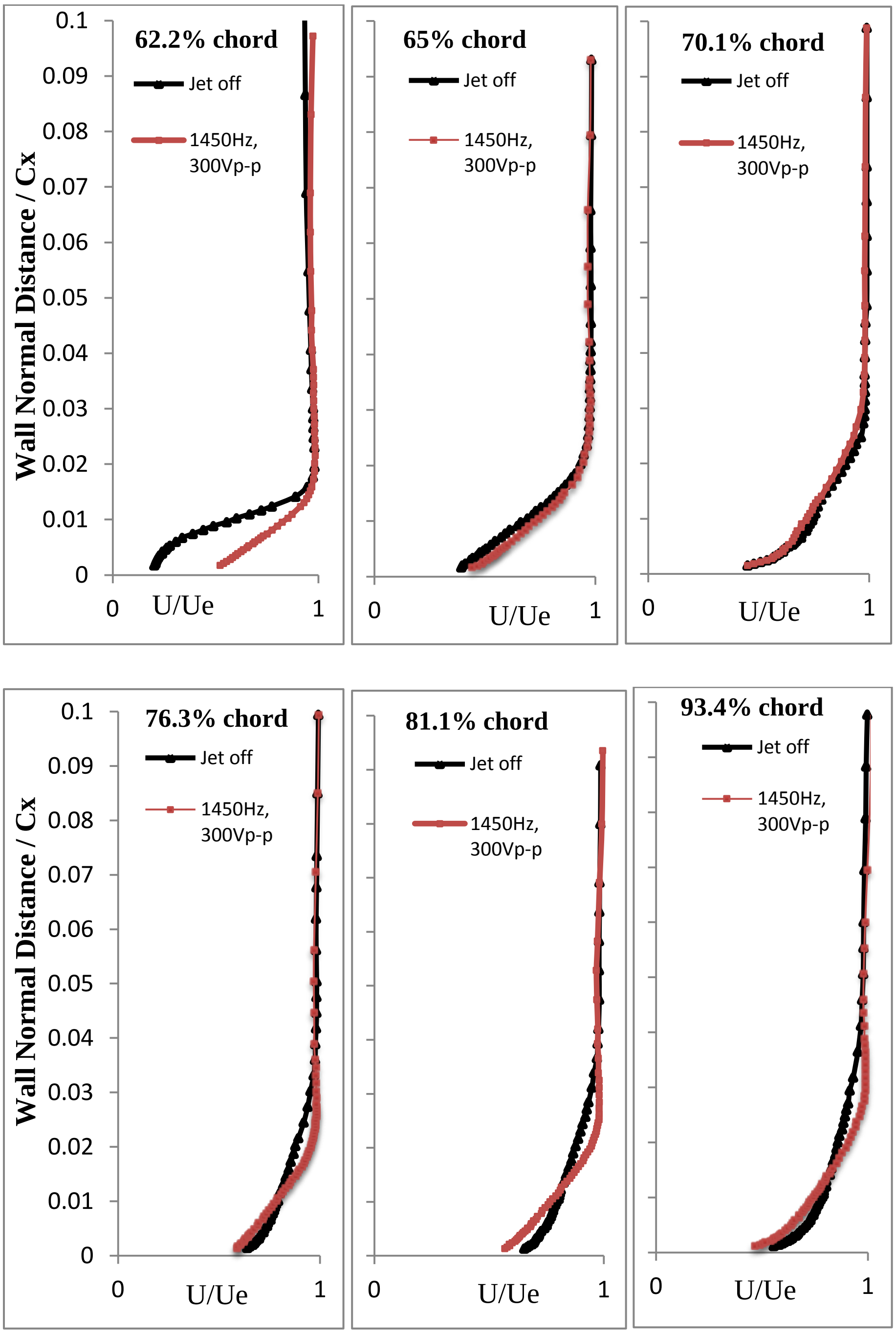

Figure 7 (continued).Comparison of the mean velocity profiles with the SJA switched on and off. Forcing amplitude is 300Vp-p and forcing frequency is 1450Hz.

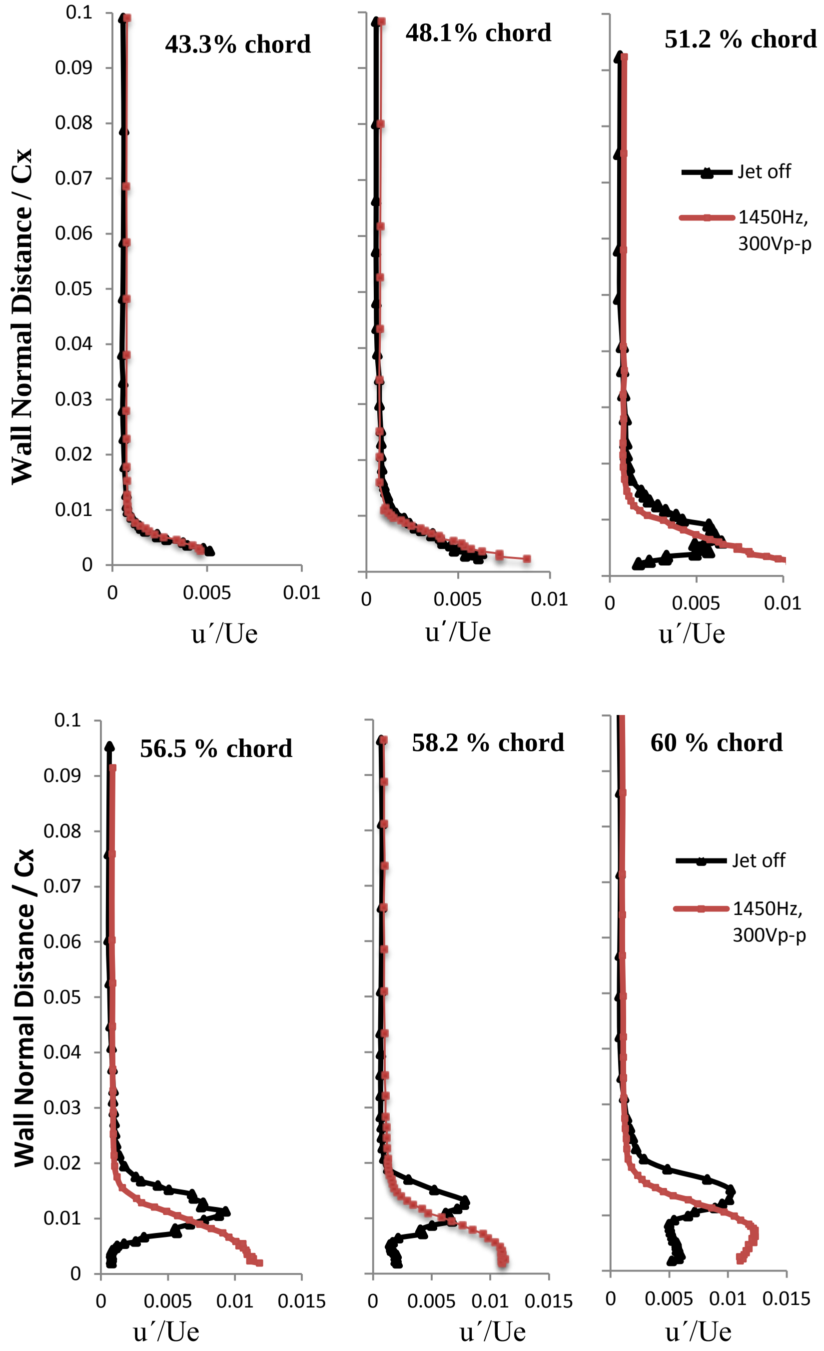

Figure 8.Comparison of the fluctuating velocity profiles with the SJA switched on and off. Forcing amplitude is 300Vp-p and forcing frequency is 1450Hz.

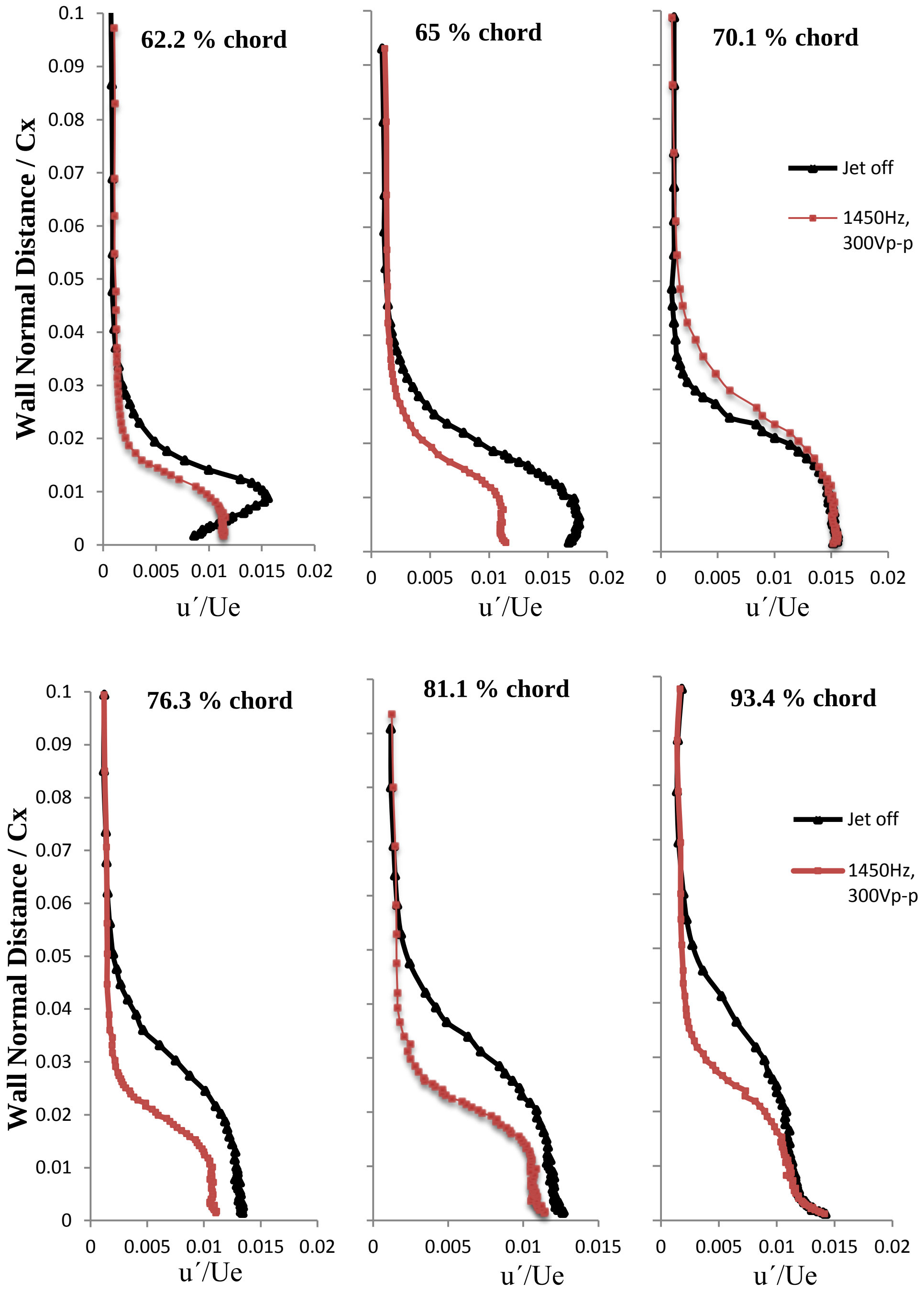

Figure 8 (continued).Comparison of the fluctuating velocity profiles with the SJA switched on and off. Forcing amplitude is 300Vp-p and forcing frequency is 1450Hz.

For the baseline case, from the Figure 7 it is seen that there is no inflection point detectable in the mean velocity profile at 43.3% chord location. Also, the velocity profile is linear near the wall and fluctuating velocities at this location are low as seen in the Figure 8. Therefore, the flow is laminar and has not separated yet. At 48.1% traverse location, although an inflection point is not clearly visible in the mean velocity profile the increased levels of fluctuating velocities in Figure 8 indicate that the flow may have separated. At the 51.2% chord location, on the other hand, an inflection point away from the wall is clearly visible in the mean velocity profile. Also, a higher amount of turbulent fluctuations are detectable at this location as demonstrated in the **Error! Reference source not found.** 8. These indications ensure that this location is on the downstream of the laminar separation point. In addition, downstream the separation point, it is observed that turbulent fluctuations increase both in the streamwise direction and normal directions. However, near the wall (airfoil surface), there occurs a region with near zero mean and fluctuating velocities. This is an indication of a dead air region where the flow is almost stationary within the separated shear layer (Sandham, 2008). Traverse locations on the 51.2%, 56.5% and 58.2% chord seem to be inside or very close to this stationary flow region. Downstream the dead air region both the mean velocities and turbulent fluctuations increase again near the wall, which may be attributed to the presence of a strong recirculation region which is known to cause a strong momentum exchange between the freestream and the flow within the separated shear layer and therefore, and to cause the separated shear layer to reattach to the surface again. Further downstream, after 70.1% chord location, it is seen that there is no peak in the fluctuating velocity profiles, also, fluctuating velocities are almost constant near the wall, which is an indication of flow reattachment around 70.1% chord location. With the reattachment, a laminar separation bubble occurs within the boundary layer and it is seen that flow develops downstream with fuller mean velocity profiles which is a typical behaviour of turbulent boundary layer flows. It is seen that baseline boundary layer measurements are in agreement with the discussions made on the behaviour of Cp curve.

With the synthetic jet actuators on, it is observed that the clearly visible inflection points present in the mean velocity profiles of the baseline case have disappeared. Also, the mean velocity profiles at each station indicate that the local boundary layer thicknesses have diminished in size; that is the shear layer is thinner than the baseline case. In addition, from the fluctuating velocity profiles in Figure 8, it is seen that there is no peak fluctuation within the shear layer away from the wall. This also indicates the absence of inflection points in the boundary layer. Furthermore, the dead air region and the strong recirculation zone, therefore the laminar separation bubble, seem to be either eliminated or diminished in size since that they are not detectable in these traversed locations.

CONCLUSION

In this study, the effect of an array of synthetic jets on the separated shear layer of a model wing that has a S809 airfoil profile was investigated at Reynolds number of 2.3x105, at zero angle of attack. Analyses of the experimental results show that the laminar separation bubble formed over the suction surface of the airfoil has been either eliminated or become very small in size through the periodic excitation generated by synthetic jet actuators. Since laminar separation bubbles decrease the aerodynamic performance of low Reynolds number airfoils, synthetic jet actuators are promising devices for improving the airfoil performance at low Reynolds numbers. In addition, since the effectiveness of synthetic jet actuators are proved at low Reynolds numbers, they can also be utilized for decreasing the cut-in speed of wind turbines, which will enable the turbine rotors to operate at low wind speeds and generate energy.

REFERENCES

[1]Amitay,M.,Smith, D.R., Kibens, V., Parekh, D. and Glezer A. (2001) Aerodynamic flow control over an unconventional airfoil using synthetic jet actuators; AIAA Journal, Vol.39, NO. 3

[2] Barlas, T.K., and van Kuik, G.A.M. Review of state of the art in smart rotor control research for wind turbines. Progress in Aerospace Sciences 46 (2010) 1–27

[2] Berg, D.E., Zayas, J.R., Lobitz, D.W., van Dam, C.P., Chow, R., and Baker, J.P. Active Aerodynamic Load Control of Wind Turbine Blades. Proc. of the 5th Joint ASME/JSME Fluids Engineering Conference, San Diego, CA., 2007.

[4] Bossanyi, E.A. The Design of Closed Loop Controllers for Wind Turbines. Wind Energy, Vol. 3, 2000, pp. 149-163.

[5] Bossanyi, E.A. Developments in Individual Blade Pitch Control. Proc. EWEA The Science of Making Torque From the Wind, Delft, the Netherlands, 2004.

[6] Larsen, T.J, Madsen, H.A., and Thomsen, K. Active Load Reduction Using Individual Pitch, Based on Local Blade Flow Measurements. Wind Energy, Vol. 8, 2004, pp. 67-80.

[7] Basualdo, S. Load Alleviation of Wind Turbine Blades Using Variable Airfoil Geometry. Wind Engineering, Vol. 29, No. 2, 2005, pp. 169-182.

[8] Mayda, E.A., van Dam, C.P., and Yen-Nakafuji, D.T. Computational Investigation of Finite Width Microtabs for Aerodynamic Load Control. AIAA Paper 2005-1185, Jan. 2005.

[9] McCormick D.C.; Boundary layer separation control with directed synthetic jets; AIAA Paper 2000-0519, 2000

[10] Sandham, N. D. (2008). Transitional Separation Bubbles and Unsteady Aspects of Aerofoil Stall. The Aeronautical J. July issue, Vol. 112, No. 1133.

[11] Stalnov, O., Kribus, A. and Seifert, A. Evaluation of active flow control applied to wind turbine blade section. J. Renewable Sustainable Energy 2, 063101 (2010)

[12] Maldonado, V., Boucher, M., Ostman, R. and Amitay, A. Active Vibration Control of a Wind Turbine Blade Using Synthetic Jets. International Journal of Flow Control. Volume 1, Number 4 December 2009

[13] Face Inc. Retrieved from http://www.prestostore.com/cgi-bin/pro23.pl?ref=thunderonline&ct=36234

[14] Hong, G. (2006) Effectiveness of Micro Synthetic Jet Actuator Enhanced by Flow Instability in Controlling Laminar Separation Caused by Adverse Pressure Gradient. Sensors and Actuators A 132 (2006) 607–615

[15] Smith, B and Glezer, A. (2005) Vectoring of Adjacent Synthetic Jets. AIAA JOURNAL Vol. 43, No. 10

[16] Milanovic, I. M. and Zaman, K. B. M. Q. (2005) Synthetic Jets in Crossflow. AIAA JOURNAL Vol.43, No. 5

[17] Schaeffler, N.W. and Jenkins, L. N. (2006) Isolated Synthetic Jet in Crossflow: Experimental Protocols for a Validation Dataset. AIAA JOURNAL Vol. 44, No. 12

[18] Tuck, A and Soria, J. (2004) Active Flow Control over a NACA 0015 Airfoil using a ZNMF Jet. 15th Australasian Fluid Mechanics Conference. The University of Sydney, Sydney, Australia 13-17 December 2004