Dept. of Mech. Eng.
CUET

Published Online April 2017 (http://www.cuet.ac.bd/merj/index.html)

Mechanical Engineering Research Journal

Vol.10, pp. 20-25, 2016

ISSN: 1990-5491

AN EXPERIMENTAL INVESTIGATION OF ACTIVE CONTROL OF FULLY SEPARATED FLOW OVER A SYMMETRICAL CIRCULAR ARC AIRFOIL

M. Mashud*and M. A. Hossain

Department of Mechanical Engineering
Khulna University of Engineering & Technology
Khulna-9203, BANGLADESH

Abstract: An experimental study of active control of fully separated flow over a symmetrical circular arc airfoil at high angles of attack was performed. Angles of attack from 10 to 25 degrees were tested. Low-power input, unsteady excitation was applied to the leading or trailing edge shear layers. The flow over sharp-edge wings is almost always separated. The control of separated flows is possible and benefits can be achieved but only in time average sense. The actuation was provided by the periodic oscillation of a 4-percent-chord flap placed on the suction side of the airfoil and facing the sharp edge. Vortex-shedding frequencies were measured and harmonic combinations selected as the applied actuator frequencies. Pressure measurements over the airfoil show that the control increased the normal force coefficient by up to 70%. This supports the idea of vortex capture in the time-averaged sense, enhancing the lift on the airfoil by managing the shear layer roll up. The results indicate the viability of the control of large-scale flow fields by exploiting the natural amplification of disturbances triggered by small-scale actuators. The application of flow control on sharp-edged aircraft wings could lead to improved maneuverability, innovative flight control and weight reduction. These can be achieved by inexpensive, low-power, rugged actuators.

Keywords: *Separated Flow, Flow Control and Lift Augmentation.*

NOMENCLATURE

L = Lift force
D = Drag force
C_p = Coefficient of pressure
V_∞ = Free stream velocity
μ_∞ = Free stream viscosity
α = Angle of attack
T = *M*aximum thickness
C = Chord length
AOA = Angle of attack

1. INTRODUCTION

In recent years there has been an enlarged attention in the flow control field, especially in aerodynamics, with the purpose of increasing lift and decreasing drag of airfoils. Wings suffer from flow separation at high angles of attack due to viscous effects, which in turn causes a major decrease in lift and increase in drag. This occurs to all types of airfoils, but especially to sharp edge wings. Over the past few decades, there has been a marked trend towards the design of fighter aircraft with low radar signature and at the same time capable of flying at supersonic regimes, maintaining high levels of maneuverability [1]. This kind of configurations involve many physical and technical limitations, setting a new challenge to the industry. Sharp edges are a common feature on these airframes, and separation can be avoided for even low angles of attack. The need for complex flap systems or swept wing configurations with stable lifting vortices is part of the tools that designers use to achieve high levels of agility and also flight at angles of attack well beyond the maximum lift. Sharp edge airfoils suffer from separation even at low angles of attack such as 8°, because the flow cannot negotiate the sharp turn at the leading edge. As the flow separates, the airfoil behaves as a bluff body. Due to this separation, a reduction in lift will be experienced by the airfoil due to the fact that the airflow on the suction side of the airfoil is

* **Corresponding author:** E-mail: mdmashud@yahoo.com, Tel: +880-1713255226, Fax: +880-41774403

separated and vortex shedding starts. The interest in this study is to try to control separated flow, not flow separation. With the implementation of flow control techniques, improvements in the lift coefficient can be obtained in a time-averaged sense. The goal of this research is to get a better insight into the flow field over these configurations, and analyze the effects of the control on the aerodynamic characteristics [3-7]. A two-dimensional circular-arc airfoil is chosen as the test bed for the analysis of flow control at high angles of attack. This is a necessary step for the understanding of the vortex lift augmentation control on the subsonic regime of supersonic, stealth wing configurations. Attached flow cannot be sustained over a sharp edge leading edge even at low angles of attack. A different means of flow control has to be put in practice: flow control of separated flows.

2. MODEL CONSTRUCTION

The airfoil model section is a symmetrical circular-arc 8 percent chord thickness airfoil. The chord length is .2032 m (8 in) resulting in an airfoil maximum thickness of 0.020066 m (0.79 in). The model spans 0.5080 m (20 in). The airfoil contour geometry is defined by a circular-arc o radius 62 cm.

The model was constructed by wood. The flap were copied with the model. Model geometry and dimensions are shown in Fig. 1. A total 38 pressure taps where installed on the airfoil, 19 on the suction side and 19 on the pressure side. These were constructed from 1 mm outer diameter. The tubes were carefully bent in their tip to be able to tightly fit in the airfoil interior. Holes were drilled and the tubes epoxied to the airfoil skin. The pressure taps are positioned with an offset angle of 10° with respect to the perpendicular of the span wise axis of the airfoil model, as shown in Figs. 2 and 3. This is done to avoid any aerodynamic interference between pressure taps, even when they were carefully installed in the airfoil contour surface.

The experiments were conducted in the Aerodynamics and Aerial Robotics Laboratory of the department of Mechanical Engineering, Khulna University of Engineering and Technology, Khulna with the subsonic wind tunnel of 1m×1m×1m rectangular test section. The wind tunnel could be operated at a maximum air speed of 43 m/s and the turntable had a capacity for setting an angle of attack of 45 degree. A small sized model is appropriate to examine the aerodynamic characteristics for the experiments. If we desire to examine the aerodynamic characteristics of a large model, a large scale wind tunnel facility is necessary for testing or the inflatable wing must be drastically scaled down to match the usual wind tunnel size violating the Reynolds number analogy requirements.

Furthermore, it would be difficult to support the inflatable wing a desirable attitude in these wind tunnel experiments. Since the vertical part of the aerodynamic force produces the lifting force necessary to suspend the load. We were mainly interested in this aerodynamic characteristics of each model. The model was placed the testing section of the wind tunnel. Then the testing procedure is started of measuring the pressure of the constructed model from the pressure sensor reading at different points from leading edge to trailing edge.

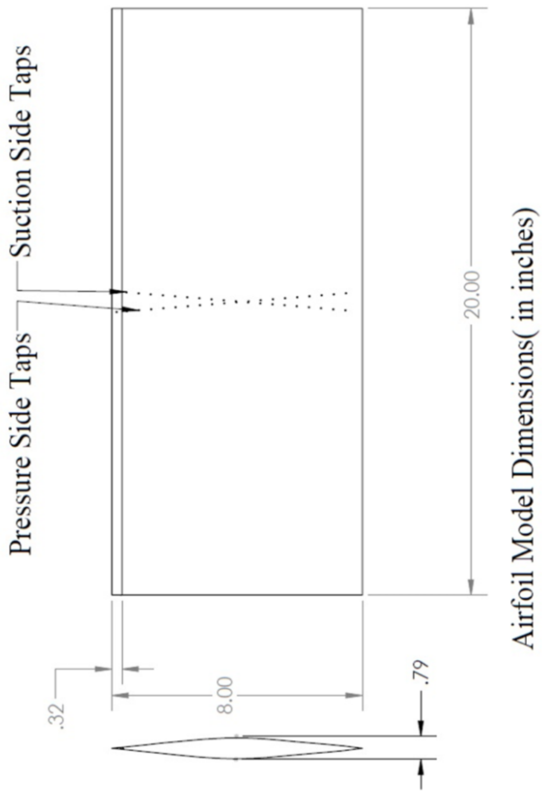

Fig. 1 Airfoil model dimensions (in inches).

Fig. 2 Constructed model.

Fig. 3 Experimental set up in the Wind tunnel.

4. METHODOLOGY

For the complete testing of the constructed wing, subsonic wind tunnel and pressure measuring sensor were used as the required apparatus. The respective model was mounted on the test section of the wind tunnel with the help of frame. Air velocity through the test section called throat was determined using Bernoulli's principle [14,15,20,21]. The pressure distribution on each surface of airfoil is expected to be symmetrical, pressure on the upper and lower surface is measured.

Wind tunnel tests in a boundary layer wind tunnel allow for the natural drag of the earth surface to be simulated. Hence, as the main aspect of the wind tunnel test is to determination of a moving object (subjected to the real working environment) for experimental consideration by regulating air flow.

Each of the pressure taping point are numbering to understand the serial of the measuring surface of the pressure. Now for airfoil and angle of attack the pressure is measured. Initially the five pressure taping points of upper surface are attached into the pressure measuring sensor. Now computer is turn on to get the value of the surface pressure of the airfoil with the help of lab view software. For room temperature the value is taken into 250 volt of the wind tunnel. For four angle of attack 10, 15, 20, 25 degree all the pressure are measured in the room temperature.

The data acquisition process is divided in two branches: pressure measurements and force measurements. The latter case can include pressure acquisition to check how the aerolastic behavior of the airfoil model affects the flow field. Since the balance still needs more research time in order to be used as a measuring tool, we will focus our attention to the measurement of pressures and dedicate a special section to the results obtained with the balance. In order to do this correctly, the balance was clamped to avoid any unsteady flow generated oscillation of the airfoil model [8-11].

The method of excitation of the shear layer was divided in two parts: perturbation of the leading edge shear layer, and perturbation of the trailing edge shear layer. Both methods use the same flap set up (i.e.: the same flap). The difference lies in the rotation of the airfoil by an angle of (180 – 2 a) degrees from the desired angle of attack.

The flap in both cases is located on the suction surface of the airfoil, and the moving sharp-edge face the leading/trailing edge. If both vortex-vortex and sound-vortex resonance is present, this should be the best configuration, as advised in the paper by Wu et al [16-19].

At first step of the experimental procedure, the constructed airfoil without flap was placed inside the testing section of the wind tunnel. By placing this, the testing section of the wind tunnel was closed to start the measurement. For different angle of attacks, pressure on the upper and lower surfaces of the airfoil was measured. After that airfoil with flap was placed inside the testing section. The airfoil with flap was placed in the testing section just like Fig. 4.

At 10° angle of attack (Leading edge flap), the testing section was closed to start the measurement. For different velocities of the wind tunnel, the lift and drag forces were measured from the scale and pressure was also measured. After this angle of attack was changed to 15° and then the lift and drag forces were measured. Next the angle of attacks were changed to measure the necessary data as the same way stated above. The velocity of the wind tunnel was controlled by a regulator attached with the wind tunnel. The ambient pressure, temperature and humidity were recorded using barometer, thermometer and hygrometer respectively for the evaluation of air density in the laboratory environment. The tests were carried out with free stream velocity of 20 m/sec.

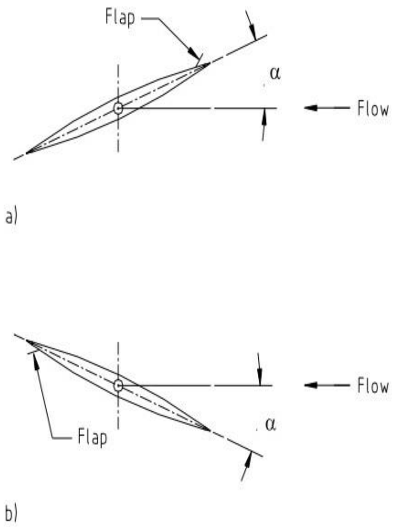

Fig. 4 Schematic of flap positions tested. a) Leading edge flap; b) trailing edge flap.

When the measurement of data had been completed, then the calculation process was started. From the measured pressure, the pressure co-efficient were calculated.

Co-efficient of pressure

$$C_p = \frac{(P - P_\infty)}{\frac{1}{2}\rho_\infty U_\infty{}^2}$$

Here,
P = Local pressure
P_∞ = Free stream pressure
U_∞ = Free stream velocity
ρ_∞ = Free stream density corresponding to the free stream pressure

Using the principal vortex shedding frequency, the Strouhal number can be computed based on the frontal height of the airfoil, yielding:

$$Str = f_s\, c \sin\alpha \,/\, U\alpha$$

This number was found to be between 0.2 and 0.22 for all angles of attack greater than 10°. Assuming the same Strouhal number, the shedding frequency for the 10° angle of attack should be in the neighborhood of 100 to 110 Hz

The unsteadiness associated with the flow around the circular-arc airfoil can be examined by presenting the evolution of the section normal force coefficient with respect to time. The normal force coefficient is calculated numerically integrating over the chord the unsteady pressure measurements taken over the surface the airfoil:

$$C_n = \int_0^1 (Cp_{suc} - Cp_{pres})\, d(x/c)$$

Here,
Cp_{suc} =Suction side pressure co-efficient
Cp_{pres}=Pressure side pressure co-efficient

The numerical integration is performed using the trapezoidal rule, and the limits of integration are reduced to the measured pressure area covered by the pressure taps.

5. RESULTS AND DISCUSSION

In order to understand the fluid dynamics of the circular-arc airfoil at high angles of attack, results with no excitation are analyzed first. These are also the basis for the comparison with the controlled cases. Due to the natural unsteadiness present in the flow over the airfoil, a simple time-average can be taken over the data obtained. The averaged values are displayed in Fig. 5 for different angles of attack. A clear constant offset out of the normal error margins is encountered for all cases.

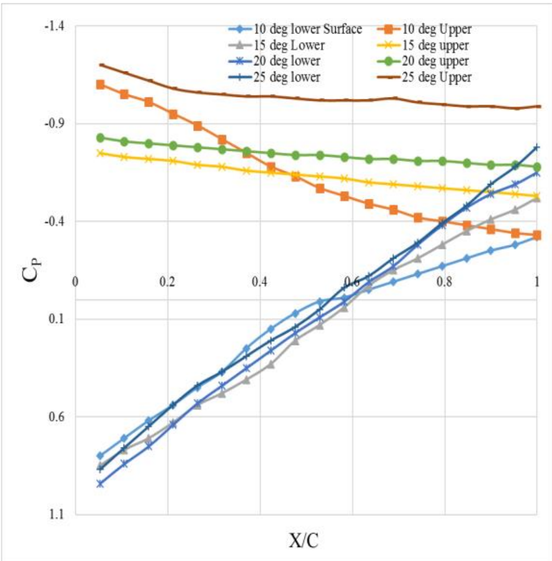

Fig. 5 Airfoil pressure coefficient distribution at different angles of attack. Suction and pressure sides. No actuation.

The figure shows that a flat top average pressure distribution, characteristic of completely separated flows is present for all angles of attack, except the case of 10 degrees. This correlates with the idea of the flow around a sharp edged airfoil: separation is inevitable at the edge and reattachment is not possible unless the airfoil is at low angles of attack. The flow physics behavior encountered is then that of a bluff body.

The stagnation point is very near to the leading edge except for the highest angle of attack. The point moves towards the leading edge as incidence is decreased, and practically lies at the edge for the lower angle s. This, and the fact of the low Reynolds number testing, makes us think that the separation on the leading edge of the airfoil is completely laminar. Since the laminar shear layer is natural unstable, transition occurs, and reattachment is only possible if the airfoil wall is close to the shear layer. That's probably the physics behind the 10 degrees case; a thickening of the shear layer due to transition to turbulence brings the fluid back to the airfoil wall, reattaching and forming a favorable flow recirculating region. If the angle of attack is increased, the reattachment point moves forward, until it reaches the trailing edge, were the airfoil completely stalls. Once the stall condition is found, vortex shedding starts to occur.

It is also not difficult to understand the need for flow control even at relatively low angles of attack. Since pressure fluctuations traduce to buffeting loads applied on the structure, at normal aircraft dynamic pressures this exerted forces are considerable in magnitude. After reviewing the basic characteristics of the base flow, we are able now to analyze the effects of excitation on the flow field around the airfoil.

Pressure coefficient distribution over the airfoil at this angle of attack is shown in Fig. 6. Figure 6 shows that both values of reduced frequency 0.5 and 1.5 promote the same lift increment, but with a difference in the vortex structure on the suction side of the airfoil. The pressure distribution on the suction side of the latter is slightly higher for the first 50% of the chord and slightly drops down towards the trailing edge. The excitation at the natural shedding frequency behaves at the opposite way, the C_p increases slightly towards the trailing edge. This implies that a different mode of vortex formation is promoted, with the latter being formed towards the trailing edge. This effect has an important implication on the moment coefficient of the airfoil. A change in excitation frequency can shift the position of the aerodynamic center, and at the same time retain the same magnitude.

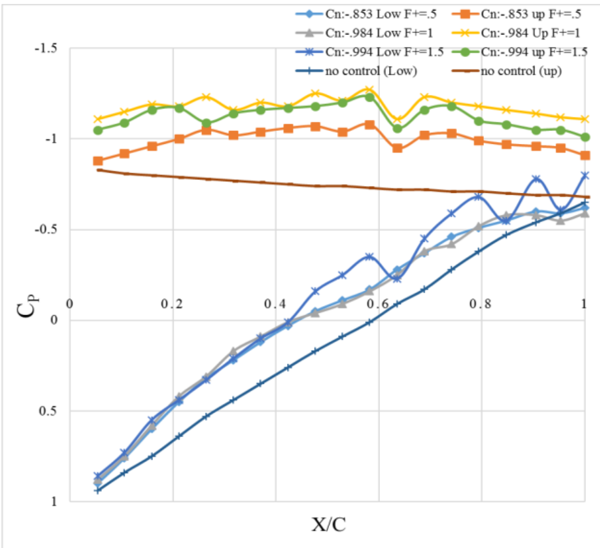

Fig. 6 Pressure coefficient distribution for controlled case. Angle of attack 20°. Leading edge excitation.

It is also important to note how the overall change in circulation due to lift augmentation is being reflected in the pressure side, by shifting the pressure coefficient somewhat downwards.

Trailing edge flap actuation does not affect the flow considerably, with a maximum lift augmentation. Vortex shedding is not modified unless for the reduced frequencies of 0.5 and 1.5, where the vortices seem likely to shed also at the sub harmonic and first harmonic of the natural shedding values. It is interesting to note that the excitation frequency of the trailing edge flap at the reduced frequency of 1.5 affects the flow in such a way that any of the main components (sub harmonic, shedding and first harmonic) subsist in the vortical structure over the airfoil. Figs. 7 show the corresponding plots for the trailing edge flap actuation.

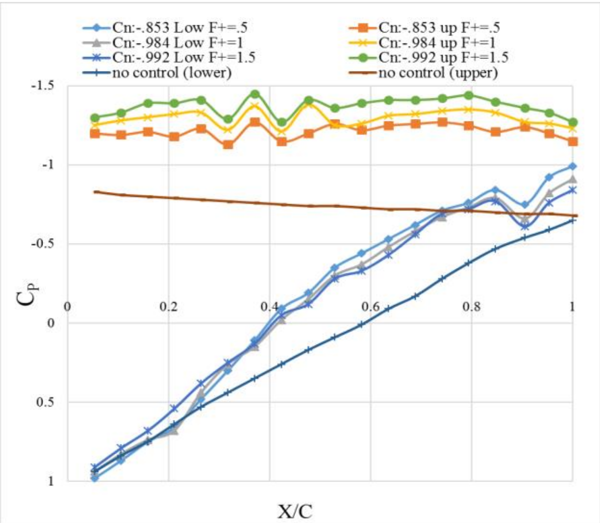

Fig. 7 Pressure coefficient distribution for controlled case. Angle of attack 20°. Trailing edge excitation.

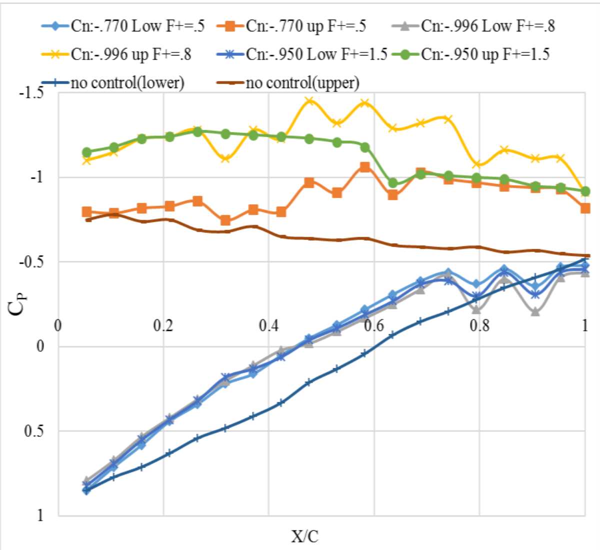

Fig. 8 Pressure coefficient distribution for controlled case. Angle of attack 15°. Leading edge excitation.

It can be seen from the figures that the actuation effect is minimal on all aspects. Pressure distribution displays a mild change around 50% and 80% of the chord. Besides that, no other effect is visible. Power spectrum density shows that no real beneficial effect is achieved over the organization of the vertical flow. One of the explanations for the lack of effectiveness is that the global instability originating at the flap triggers a resonant mode with the leading edge shear layer, shifting the rolling up mode at a different frequency, but not really strengthening the vortex structure. The most probable explanation for this behavior is the simple fact that the shear layer is away from the flap, and cannot effectively reach it. The 15° angle of attack generates the maximum lift increase on the airfoil. Fig. 8 shows the change in the relevant parameters with actuation frequency for the 15° case.

As it can be seen from the pressure distribution over the airfoil, reduced normal forces lead to raising of the suction side pressure distribution, i.e. increasing lift. It is hard to tell, but it would seem that a vortex positioned at half the chord of the airfoil gains strength with the excitation levels. The remarkable point is that an average reattachment close to the trailing edge appears to be present.

This implies that at 10° incidence the flow requires a perturbation to trigger the shedding of the vortices on the suction side of the airfoil. A stable mode can be converted to an unstable more efficient mode.

Normal force coefficient increments are not as impressive as on the 15° case, but overall lift is augmented. Fig. 9 shows the effects of excitation in this particular case.

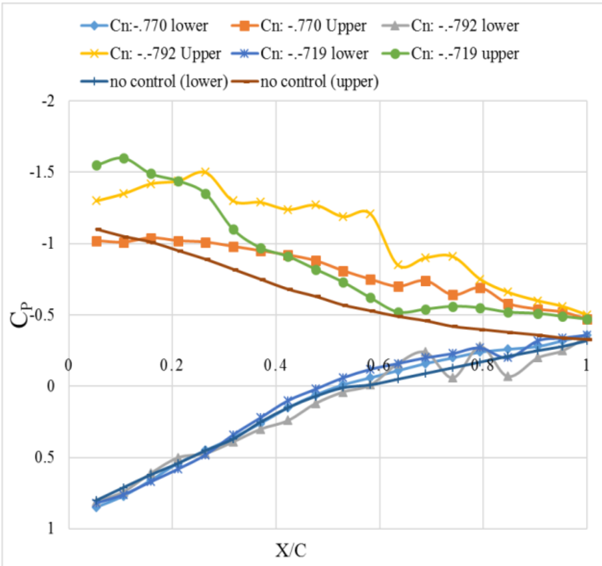

Fig. 9 Pressure coefficient distribution for controlled case. Angle of attack 10°.

Leading edge excitation Pressure distributions are also unexpected and unusual. While the highest reduced frequencies seem to promote a fast reattachment of the flow, the optimum reduced frequency creates a vortex in the average sense over the suction surface that increases the suction force. This can be seen in Fig. 9. Flow is reattached also in the average sense, but at a further downstream point [2,12]. The plot of the airfoil pressure coefficient with respect to time, shows again that excitation increases oscillation amplitude.

6. CONCLUSION

The serration in the leading edge of an airfoil facilitates the reduction and potential elimination of tonal noise for an airfoil. The leading edge serration was effective in reducing separated flow on the model. Separated flow progressed with the increase of angle of attack. The serration delayed the separated flow to higher angles of attack and increased maximum lift and angle of attack for maximum lift of the model. The drag at low angles of attack was not affected and at high angles of attack the drag was reduced. Serration spacing or gap affected the airfoil lift.

7. ACKNOWLEDGEMENT

This project was conducted in the Aerodynamics & Aerial Robotics Laboratory, Department of Mechanical Engineering, Khulna University of Engineering & Technology as a part of thesis project and authors are grateful to the authority of KUET.

REFERENCES

[1] M. Mashud, M. M. Sarwar, M. A. G. Mollah and M. F. Hossain, "Experimental Study of Separated Flow Control over a Sharp-Edged Arc Airfoil", International Journal of Engineering & Technology IJET-IJENS Vol: 09, No. 10, Vol. 123, pp 492-500, 2001.

[2] M. Mashud and M. F Hossain, "Experimental Study of Flow Separation Control of an Airfoil by Suction and Injection", Proceedings of the 13th Asian Congress of Fluid Mechanics, 17-21 December 2010, Dhaka, Bangladesh.

[3] S. Miranda, "Active Control of Separated Flow over a Circular-Arc Airfoil" Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University, May 8, 2000 , Blacksburg, Virginia

[4] F. D. Gregorio and G. Fraioli, "Flow control on a high thickness airfoil by a trapped vortex cavity", 14th IntSymp on Applications of Laser Techniques to Fluid Mechanics Lisbon, Portugal, 7-10 July, 2008.

[5] A. Khodadoust and A. Washburn "Active Control of Flow Separation on a High-Lift System with Slotted Flap at High Reynolds Number", American Institute of Aeronautics and Astronautics.

[6] Y. Tian and L. N. Cattafesta III "Adaptive Control of Separated Flow", 44th AIAA Aerospace Sciences Meeting and Exhibit, 9 - 12 January 2006, Reno, Nevada, AIAA 2006-1401

[7] J. B. Barlow, W. H. Rae and A. Pope, "Low-Speed Wind Tunnel Testing", 3rd edition, Wiley-Interscience publication, John Wiley & Sons, New York,1999.

[8] W. J. Bursnall, "Experimental Investigation of the Effects of Vortex Generators on the Maximum Lift of a 6-Percent-Thick Symmetrical Circular-Arc Airfoil Section", NACA RM L52G24, 1952.

[9] R. C. Chang, F. –B. Hsiao and R. –N. Shyu, "Forcing Level Effects of Internal Acoustic Excitation on the Improvement of Airfoil Performance", J. of Aircraft, Vol. 29, No. 5, pp. 823-829, 1992.

[10] A. Crook, A. M. Sadri and N. J. Wood, "The development and Implementation of Synthetic Jets for the Control of Separated Flow", AIAA 99-3176, 1999.

[11] H. E. Fiedler, "Control of Free Turbulent Shear Flows", In Flow Control: Fundamentals and Practices (ed. Gad-el-Hak, M., Pollard, A., Bonnet, J. P.), pp. 335-429, Springer Lecture Notes in Physics, New Series Monographs, M53, and Springer-Verlag, Berlin, 1998.

[12] M. Gad-el-Hak, "Introduction to Flow Control", In Flow Control: Fundamentals and Practices (ed. Gad-el-Hak, M., Pollard, A., Bonnet, J. P.), pp. 1-107,Springer Lecture Notes in Physics, New Series Monographs, M53, Springer-Verlag, Berlin,1998.

[13] Y. He and L. Kral, "Post-Stall Control on an Airfoil Using Localized Jet Actuators", AIAA 2000-0408, 2000.

[14] S. L. Yang and G. R. Spedding, "Separation Control by External Acoustic Excitation at Low Reynolds Numbers", AIAA Journal Vol. 51, No. 6, June 2013.

[15] F. –B. Hsiao, C. -F. Liu and J. –Y. Shyu," Control of Wall-Separated Flow by Internal Acoustic Excitation", AIAA Journal, Vol. 28, No. 8, pp.1440-1446, 1990.

[16] F. –B. Hsiao, R. –N. Shyu and R. C. Chang," High Angle-of-Attack Airfoil Performance Improvement by Internal Acoustic Excitation", AIAA Journal, Vol. 32, No. 3, pp. 655-657, 1994.

[17] F. –B. Hsiao, T. -Z. Wang and Y. Zohar, " Flow separation Control of a 2-D Airfoil by a Leading-Edge Oscillating Flap", Intl. Conf. Aerospace Sci. Tech., Tainan, Taiwan, Dec. 6-9, 1993.

[18] C.-M. Ho and P. Huerre, "Perturbed Free Shear Layers", Ann. Rev. Fluid Mech., Vol. 16, pp. 365-424, 1984.

[19] C. -M. Ho, "Local and global dynamics of free shear layers", In Numerical and Physical Aspects of Aerodynamic Flows (ed. T. Cebeci), pp. 521, Springer-Verlag, 1981.

[20] M. Kiya, O. Mochizuki and N. Suzuki, "Separation Control by Vortex Proyectiles", AIAA 99-3400, 1999.

[21] A. Roshko, "On the Drag and Shedding Frequency of Two-Dimensional Bluff Bodies", NACA TN 3169, 1954.