EFFECTIVENESS OF SYNTHETIC JET ACTUATORS FOR SEPARATION CONTROL ON AN AIRFOIL

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To my beloved parents (Allahyarham Haji Dahalan Bin Sungip and Hajah Thalathiah Binti Hj. Ahmad), wife (Zahabiah Binti Kamsol) and children (Nurizyan, Nur Izzati and Luqman Hakim)

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ABSTRACT

The aerodynamic performance of an airfoil could be improved by controlling flow separation using active flow control techniques. In this study, a synthetic jet actuator (SJA) based on piezoelectric diaphragm has been developed. The selection of the SJA was due to their advantages in being lightweight, no external air supply required, simple system assembly, fast time response, low power consumption, easy installation, low cost and relatively small in size. Basically, the performance of the SJA depends on the specification and configuration of jet orifice, cavity, and oscillating membrane. The parameters studied include waveform signal, frequency, voltage, cavity and orifice physical characteristics. Final design and geometry of the SJA were determined based on these parameters. The SJA design with the best performance has been developed to generate sufficient air jet velocity to control flow separation. The experimental results measured by a hot-wire anemometer show that the maximum jet velocity obtained by the SJA with circular and slot orifice were 41.71 m/s and 35.3 m/s at an applied frequency of 900 Hz and 1570 Hz respectively. Next, the selected SJA was embedded into the wing with NACA 0015 airfoil and placed at 12.5% chord from the leading edge. Wind tunnel testing was conducted for stationary and oscillating airfoil conditions, with and without the SJA. The unsteady aerodynamic loads were calculated from the surface pressure measurements of 30 ports along the wing chord for both upper and lower surfaces. The airfoil was tested at various angles of attack at a free-stream velocity of up to 35 m/s corresponding to a Reynolds number of 1.006×10^6. Specifically for an oscillating airfoil, the reduced frequency, *k*, was varied from 0.02 to 0.18. The results of an airfoil with SJA showed that the C_{Lmax} and stall angle increased up to 13.94% and 29% respectively. Based on the results obtained, the SJA has an excellent capability to control the flow separation with delaying the stall angle, increasing the maximum lift, reducing the drag and delaying the intense nose down pitching moment.

ABSTRAK

Prestasi aerodinamik sebuah aerofoil boleh diperbaiki dengan mengawal pemisahan aliran menggunakan teknik kawalan aliran aktif. Dalam kajian ini, penggerak jet sintetik (SJA) berasaskan gegendang piezoelektrik telah dibangunkan. Pemilihan SJA adalah kerana kelebihannya iaitu ringan, tiada bekalan udara luar yang diperlukan, pemasangan sistem yang mudah, masa tindak balas yang cepat, penggunaan kuasa yang rendah, kos yang rendah dan bersaiz kecil. Pada dasarnya, prestasi SJA bergantung kepada spesifikasi dan konfigurasi orifis jet, rongga, dan membran berayun. Parameter-parameter yang dikaji termasuk isyarat bentuk gelombang, frekuensi, voltan dan juga ciri-ciri fizikal rongga dan orifis. Reka bentuk dan geometri muktamad SJA ditentukan berdasarkan kepada parameter-parameter ini. Reka bentuk SJA dengan prestasi yang terbaik telah dibangunkan untuk menghasilkan halaju jet udara yang mencukupi untuk mengawal pemisahan aliran. Keputusan eksperimen yang diukur menggunakan anemometer wayar-panas menunjukkan bahawa halaju jet maksimum yang diperoleh daripada SJA berorifis bulat dan slot adalah masing-masing 41.71 m/s dan 35.3 m/s pada frekuensi kenaan 900 Hz dan 1570 Hz. Seterusnya, SJA yang dipilih telah dipasang di dalam sayap beraerofoil NACA 0015 dan diletakkan pada 12.5% rentas dari pinggir hadapan sayap. Ujian terowong angin telah dijalankan dalam keadaan aerofoil tidak bergerak dan berayun dengan dan tanpa SJA. Beban aerodinamik tak mantap dikira daripada pengukuran tekanan permukaan pada 30 lokasi di sepanjang rentas sayap untuk kedua-dua permukaan atas dan bawah. Aerofoil telah diuji pada pelbagai sudut serang dan pada halaju aliran bebas sehingga 35 m/s sepadan dengan nombor Reynolds 1.006×10^6. Khusus untuk aerofoil berayun, frekuensi terkurang, k, berubah antara 0.02 - 0.18. Keputusan ujikaji aerofoil dengan adanya SJA menunjukkan bahawa C_{Lmax} dan sudut pegun masing-masing meningkat sehingga 13.94% dan 29%. Keputusan yang diperolehi menunjukkan bahawa SJA mempunyai keupayaan yang cemerlang untuk mengawal pemisahan aliran dengan melewatkan sudut pegun, meningkatkan daya angkat maksimum, mengurangkan seretan dan melambatkan kejatuhan kuat pada momen anggul.

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A	-	Orifice area (m^2)
c	-	Chord of airfoil (m)
C_D	-	Drag coefficient
C_L	-	Lift coefficient
C_M	-	Pitching moment coefficient
C_P	-	Pressure coefficient
C_x	-	Parallel force acting on the airfoil with respect to chord line
C_y	-	Normal force acting on the airfoil with respect to chord line
$C\mu$	-	Jet momentum coefficient
dA_x	-	Cell area in x (dimensionless)
dA_y	-	Cell area in y (dimensionless)
d_c	-	Cavity height (m)
d_o	-	Orifice or slot diameter (m)
E	-	Modulus Young
f	-	Applied/oscillating frequency (Hz)
f_H	-	Helmholtz frequency (Hz)
f_D	-	Resonance frequency (Hz)
F^+	-	Non-dimensional frequency
h_c	-	Cavity thickness/height (m)
h_o	-	Orifice depth/thickness (m)
l_c	-	Cavity length (m)
L	-	Orifice length (m)
L_o	-	Stroke length
L_s	-	Non-dimensional stroke length
$\dot{m}$	-	Incompressible flows
P	-	Pressure at the measurement point (Pa)

P_∞	-	Free stream static pressure (Pa)
Po	-	Total pressure (Pa)
q_∞	-	Free stream dynamic pressure (Pa)
Sr	-	Strouhal number
St	-	Stroke number
r_D	-	Diaphragm radius
R_e	-	Reynolds number (normal)
R_{ej}	-	Jet Reynolds number
t_D	-	Diaphragm thickness (m)
T_o	-	Time or inverse of the oscillating frequency
U_j	-	Jet velocity (m/s)
V	-	Cavity volume (m^3)
V_∞	-	Free stream or flight velocity (m/s)
w_c	-	Cavity width (m)
□	-	Angle of attack (deg)
α (t)	-	Instantaneous angle of attack (deg)
α_{mean}	-	Mean angle of attack (deg)
α_{amp}	-	Amplitude of airfoil oscillation (deg)
$k = \frac{\omega c}{2V_\infty}$	-	Reduced frequency
$\omega = 2\pi f$	-	Angular velocity (rad/s)
υ	-	Fluid kinematic viscosity
ρ	-	Air density

Abbreviations

SJA	-	Synthetic jet actuator
RMS	-	Root-Mean-Square
UTM	-	Universiti Teknologi Malaysia
MLST	-	Malaysian low speed tunnel

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The wings, horizontal and vertical tail surfaces of an aircraft, wind turbine blades, propellers and helicopter rotor blades are made from various airfoils shape. The function of the airfoil is to generate lift force when moving through the air. Lift is usually increased linearly with angle of attack up to a stalling angle when the lift may reduce or drop rapidly at stall phenomena. The stall of an airfoil is due to the separation of the flow field over its surface. Flow separation over an airfoil occurs because of the flow in the boundary layer lacks the momentum to overcome the adverse pressure gradient and usually causes a significant loss of lift and an increase in drag, which limits the aerodynamic performance of an aircraft (Miller, 2004; Rehman and Kontis, 2006). The maximum lift and stall characteristics of an airfoil affect many performance aspects of air vehicles. For examples, take-off and landing distance, maximum and sustained turn rates, climb and glide rates, and a flight ceiling of the fixed wing aircraft (Corke et al., 2002). The maximum lift can be achieved based on the ability of the flow to follow the airfoil curvature. But to obtain a better maximum lift is limited for the typical airfoil. When an aircraft is taking off or landing, the wing requires a higher lift coefficient to maintain the desired flight at low speeds. If a lower stalling speed is needed, higher values of the maximum lift coefficient must be achieved. The aim is that the aircraft can take off or land on a shorter distance and does not require a long runway. Delaying or eliminating separation entirely would increase lift and reduce drag, hence increasing the aerodynamic performance of lifting surfaces (Rehman and Kontis, 2006) mention about different types of stall including dynamic stall.

Dynamic stall is a phenomenon that also affects airfoil, wing, rotor and it occurs when there is a sudden gust of the wind, a very rapid maneuver or an excessively steep bank are entered, and at any airspeed and attitude. It is an unsteady flow condition which refers to the stalling behavior of an airfoil when the angle of attack is changing rapidly with time. This phenomenon can appear in a variety of situations such as with helicopter rotor blades, a rapidly maneuvering aircraft, turbo-machinery cascades or wind turbines.

The aerodynamic performance of airplanes, helicopters, and road vehicles can be improved by controlling the air flow over their working surfaces, for example, wings and rotary blades, especially when operating at high angles of attack. This controlled condition occurs when the boundary layer and the shear flow on the suction surface are manipulated until the separation region is reduced.

In order to delay the boundary layer separation, the momentum of the near-wall fluid needs to be increased, which mean the increment of the near-wall velocity gradient and wall shear stress. Collis et al. (2004) had suggested three methods to enhance the near-wall momentum, which creates the energy of the fluid, removing low momentum fluid, and re-distributing momentum across the boundary layer. To supply the auxiliary power to the surface, blowing process is required in the vicinity of the wall. Also, the low momentum fluid in the near-wall region can be removed by a suction process in the region of an adverse pressure gradient. However, momentum redistribution depends on the formation of coherent vorticity, which can absorb high momentum fluid from the outer region of the boundary layer into a near-wall region, which then makes the boundary layer attach on the surface (Gad el Hak, 2000).

There are two types of devices used in the controlling of the air flow, which is an active and a passive flow control devices. In improving the air flow properties, the devices are usually attached to a suitable location of the vehicles. Many flow control devices have been produced and tested by previous researchers to ensure that they work as intended (Tuck and Soria, 2004).

Devices performance is limited at the location of separation as the boundary layer separation contributes to significant energy losses. For an aerodynamic body, flow separation adds to the increment of drag. Therefore, separation control plays a vital role in the performance of an aerodynamic body, in order to delay or eliminate the flow separation. Some advantages of flow separation control on an aircraft are increased lift for greater payload, reduced engine power thus reducing fuel consumption and noise at take-off, shorter runways and reduce approach speed (Gad el Hak, 2000). A lot of money spent in fuel consumption can be saved, and fewer greenhouse gasses are emitted, as the performance of aircraft is improved.

Active flow control refers to the process of expending energy to modify the flow (Donovan et al., 1998). This device is distinct from passive techniques where flow control is provided without expending energy through means such as geometric shaping. One of the main advantages of active, rather than passive flow control is that the device can be switched on and off when required (Tuck and Soria, 2004). However, active control devices usually involve complexity in their design, incur a higher cost to manufacture and need a power supply to operate. These factors are sometimes the reason that prevents the use of active control. For this reason, many researchers have focused on designing better active flow control devices that are easy to manufacture, small in size and require little power to operate.

Several works have been carried out to control the flow separation on an airfoil. Separation delay also will permit the operation of an airfoil at higher angles of attack. Improving the aerodynamic performances of an airfoil can be achieved by controlling the separation using flow control techniques (Carr and McAlister, 1983;

Tuncer and Sankar, 1994; Bangalore and Sankar, 1996; Lorber et al., 2000; Geissler et al., 2000; Magill et al., 2001; Chrisminder et al., 2006; Song et al., 2013). Most active flow control techniques that were proposed previously were based on jet suction or blowing. However, there are some difficulties in implementing such devices into efficient airfoils, since some of the designs are very complicated, is heavy and costly, and need a significant amount of power and room for air supply.

The synthetic jet actuator (SJA) is one of the flow control technology that was also used to control the flow separation. Several studies have been conducted to observe the effectiveness of SJA to control the separation (Chang et al., 1992; Seifert et al., 1993 and 1996; Smith and Glezer, 1998; Gilarranz and Rediniotis, 2001; Kim, 2005; Gilarranz et al., 2005; Durrani and Haider, 2011; Jabbal, 2012; Koopmans and Hoeijmakers, 2014). However, most of the studies were based on a piston driving mechanism that produces a complex system when embedded in the airfoil. The drivers using piston are not the most optimum choice for use in confined spaces and are heavier than piezoelectric and acoustic diaphragms although they are more powerful and reliable (Tuck and Soria, 2008; Kim, 2005; Gilarranz et al., 2005). This study focuses on piezoelectric diaphragms.

The selection of piezoelectric diaphragms are due to their light weight, no need for external air supply, without complex plumbing, rapid time response, simple structure, low power consumption, easy installation, low cost, relatively small in size and only requires electrical power to generate the jet (Ugrina, 2007). This type has a great potential as an active control device and is very suitable to implement in aviation and automotive industry, especially to improve the aerodynamic performance of aircraft, helicopters, and road vehicles.

The new design of the SJA needs certain parameters and characteristics before can be successfully used to influence the separated flow. Tiny literature exists the complete data of the SJA design. Some users are just using the existing SJA and install them in the system or wing but did not mention the detail about the SJA.

Researchers would have trouble if they did not know the behavior of SJA regarding critical parameters used to generate sufficient jets such as forcing frequency, voltage supply, an electrical signal, the shape and volume of the cavity, orifice diameter, etc. The process of fabrication and assembly the component of the SJA also plays a significant role in producing good pulsed jet. Hence, this study tries to understand the overall aspect of the SJA designs based on the piezoelectric diaphragms and will investigate and optimize the characteristics from the beginning. Tests will be conducted to obtain the best characteristics of SJA that is suitable to reapply as an active flow control devices. Finally, the actuators will be embedded in the wing then will be tested in the wind tunnel at stationary and oscillating conditions to investigate its effectiveness control the flow separation.

Previously, most of the studies on the control of flow separation on an airfoil only focus on a stationary condition (Morel-Fatio *et al*., 2003; Holman *et al*., 2003; Hui *et al*., 2014; Zhao *et.al*., 2016; Montazer *et al*., 2016; Boualem *et al*., 2017). A few researchers involved the oscillating conditions with emphasis on numerical analysis (Lorber *et al*., 2000; McCormick *et al*., 2001; Rehman and Kontis, 2006; Joshua *et al*., 2013). Mean that oscillating airfoil with SJA based on piezoelectric diaphragm has not been well studied experimentally. Therefore, the experimental works need to be done to verify the performance of SJA in both stationary and oscillating conditions.

1.2 Objectives of Study

Recent works discussed in the literature section show that several studies have been conducted to observe the effectiveness of flow control devices to delay the flow separation on an airfoil. Thus, this study was designed the SJA based on piezoelectric diaphragms being one of the flow control devices for that purposes. The objectives of this study are:

i. To investigate and characterize the effects of synthetic jet actuator parameters based on piezoelectric diaphragm through experiments.
ii. To design a synthetic jet actuator that can be employed effectively to delay flow separation and stall on an airfoil.
iii. To investigate the aerodynamic characteristics (i.e., coefficients of lift, drag and pitching moment) of an airfoil with and without the synthetic jet actuator.
iv. To determine the performance of synthetic jet actuator in controlling flow separation for both stationary and oscillating airfoil.

Additional knowledge and improved understanding are needed to design the SJA, especially to obtain optimum efficiencies to apply it to the full-scale vehicles. Some questions must be answered regarding the application of the SJA based on the piezoelectric diaphragm. The questions are: what parameters are involved?; what size of cavity to be used?; what orifice geometry is the best?; what is the impact of frequency, voltage, and waveform to the actuators?; are the jet generated by the SJA is sufficient to control the flow separation?; where the SJA should be placed?; how the SJA is installed in the airfoil?; and how the SJA control the flow separation. Therefore, it is important to design the SJA that is capable to produce an efficient synthetic jet to control the flow separation and suitable to be integrated into the wing designs.

Apparently, the effects of static and dynamic motion need to be studied. Accordingly, the experimental techniques will be proposed to evaluate the effectiveness of the SJA to delay the flow separation of an airfoil and to quantify the aerodynamic characteristics for both stationary and oscillating conditions.

1.3 Significant of Study

The first scientific impacts are documentation and improved understanding of the design of the SJA to control the flow separation. The significant of the study are:

i. Determination and characterization of the SJA parameters based on piezoelectric diaphragms by experiments. Analytical and numerical analysis were only exploring the prediction of air jet velocity. The experimental method shows the real air jet velocity because every single design of the SJA gives different air jet velocity at a different applied frequency.

ii. Optimization the relationship and coupling effects between cavity and orifice of SJA parameters to generate sufficient air jet velocity for flow separation control by determining the proper operational waveform, frequency, and voltages of the SJA. So far the results shown in the literature are not enough, incomplete and a bit confusing.

iii. Development of the experimental test rig to investigate the flow separation control on an airfoil using SJA to quantify the aerodynamic characteristics such as lift, drag and pitching moment coefficients for both stationary and oscillating conditions.

iv. The correlation between the jet velocity and the cross flow around the airfoil to delay the separation. Thus, improve the aerodynamic performance with delays stall, increase the maximum lift and reduce the drag and pitching moment. Finally, proving that the effectiveness of SJA to control the flow separation.

REFERENCES

Agarwal, G., Rediniotis, O.K. and Traub, L.W. (2008), "An Experimental Investigation on the Effects of Pulsed Air Blowing Separation Control on NACA 0015", 46th AIAA Aerospace Sciences Meeting and Exhibit , Reno, Nevada, *AIAA 2008 – 737.*

Alien, M. G. and Glezer, A. (1995), "Jet Vectoring Using Zero Mass Flux Control Jets," AFOSR Contractor and Grantee Meeting on Turbulence and Internal Flows, Wright Patterson AFB, May

Amitay, M., Kibens, V., Parekh, D., and Glezer, A. (1999), "The Dynamics of Flow Reattachment over a Thick Airfoil Controlled by Synthetic Jet Actuators", *AIAA Paper 99-1001*

Aviation partners, Inc, http://www.aviationpartners.com/blendedwinglets.html

Azar, K. (2003), "Thermal Measurements in Electronics Cooling", Electronics Cooling Magazine, May.

Bangalore, A. and Sankar, L. N. (1996). "Numerical Analysis of Aerodynamic Performance of Rotors with Leading Edge Slats," *Journal of Computational Mechanics*, Vol. 17, pp. 335-342.

Bailo, K., Brei, D. and Calkins, F. (2000), "Investigation of PVdf Active Diaphragm for Synthetic Jets", Proceedings SPIE Vol. 3991, pp. 220-231.

Blevins, R.D. (1979), "Formulas for natural frequency and mode shape", 2nd ed. New York: Von Nostrand Reinhold Company, pp.429.

Boualem K., Azzi A. and Yahiaoui T., (2017), "Numerical Investigation of Improved Aerodynamic Performance of a NACA 0015 Airfoil Using Synthetic Jet", *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* Vol: 11, No: 3

Bryant, R., Effinger, R., Isaiah, A., Copeland, B., Covington, E. and Hogge, J. (2004), "Radial Field Piezoelectric Diaphragms", *Journal of Intelligent Material Systems and Structures*, Vol. **15**, pp 527 – 538.

BVMjets.com, http://www.bvmjets.com/pages/kits/mig-15e.html

Campbell, J.S., Black, W.Z., Glezer, A. and Hartley, J.G. (1998), "Thermal Management of a Laptop Computer with Synthetic Air Microjets", Intersociety Conference on Therm. Phenomenon, IEEE, pp. 43-50.

Cappelleri, D.J., Frecker, M.I., Simpson, T.W. and Snyder, A. (2002), "Design of a PZT Bimorph Actuator Using a Metamodel-Based Approach," *Transactions of the ASME*, Vol 124, pp 354-357.

Carl, Z. (2012), "Some Basic Principles of Wind Tunnel Design"Advanced Thermal Solutions (Wind Tunnel), July 17, Inc. 89-27 Access Road, Norwood, MA 02062, USA.

Carr, L.W., McAlister, K.W. and McCroskey, W.J. (1977), "Analysis of the Development of Dynamic Stall Based on Oscillating Airfoil Experiments". NASA Technical Note, Ames Research Center and U.S. Army Air Mobility R&D Laboratory, Moffett Field, Calif. 94035.

Carr, L. W. and McAlister, K. W. (1983). "The Effects of Leading Edge Slat on the Dynamic Stall of an oscillating Airfoil," *AIAA Paper 85-2533*.

Castro, D.N. (2002), "Numerical Modelling of Synthetic Jet in Quiescent Air with Moving Boundary Conditions", Bachelor of Science in Mechanical Engineering, Virginia Commonwealth University, Richmond, Virginia.

Cerón-Muñoz, H.D., Catalano, F.M. and Coimbra, R.F. (2008), "Passive, Active and Adaptative Systems For Wing Vortex Drag Reduction", 26th International Congress Of The Aeronautical Sciences (ICAS 2008).

Chang, R., Hsiao, F. and Shyu, R. (1992),"Forcing Level Effects of Internal Acoustic Excitation on the Improvement of Airfoil Performance", *Journal of Aircraft*, 29 (5), 823-829.

Chatlynne, E., Rumighy, N., Amitay, M. and Glezer, A. (2001),"Virtual Aero-Shaping of a Clark-Y Airfoil using Synthetic Jet Actuators", *AIAA Paper 2001-0732*.

Chen, F., Beeler, G. and Bryant, R. (2000), "Development of Synthetic Jet Actuators for Active Flow Control at NASA Langley", *AIAA Paper 2000- 2405*

Chen, F. and Beeler, G. (2002), "Virtual Shaping of a Two-dimensional NACA 0015 Airfoil Using Synthetic Jet Actuator", *AIAA Paper 2002-3273*

Chrisminder, S., David, J., Anastassios, K., and Vahik, K. (2006), "Control of Rotorcraft Retreating Blade Stall Using Air-Jet Vortex Generators", *Journal Of Aircraft*, Vol. 43, No. 4, July–August.

Collis, S., Joslin, R., Seifert, A., and Theofilis, V. (2004), "Issues in active flow control: theory, control, simulation, and experiment", *Progress in Aerospace Sciences*, 40 (4–5), 237-289.

Corke, T. C., Jumper, E. J., Post, M. L., Orlov, D., and McLaughlin, T. E., (2002) "Application of weakly-ionized plasmas as wing flow-control devices." *AIAA Paper 2002-0350*

Crook, A., Sadri, A. M., and Wood, N. J. (1999), "The Development and Implementation of Synthetic Jets for the Control of Separated Flow," *AIAA Paper 99-3176.*

Crook, A. (1999), "The Control of Turbulent Flows Using Synthetic-Jet Flowfields," *AIAA Journal*, Vol. 37, No.8, pp. 919-27.

Crook, A. and Wood N. (2001), "Measurements and Visualizations of Synthetic Jets", *AIAA Paper 2001-0145*.

Dahalan M.N., Mansor S., Shaharudin M.H. and Ali A. (2012), "Evaluation of Synthetic Jet Actuators Design Performance", *Aircraft Engineering and Aerospace Technology : An International Journal*, ISSN 1748-8842, Vol 84, Number 6, pp 390-397

Dahalan M.N., Mansor S., Ali M.F. (2015)," Study The Orifice Effects Of A Synthetic Jet Actuator Design", *Jurnal Teknologi (Sciences & Engineering)* Universiti Teknologi Malaysia , 77:8, pp 99–105

Donovan, J.F., Kral, L.D. and Cary A.W. (1998), "Active flow control applied to an airfoil", *AIAA Paper 98-0210.*

Durrani, N. and Haider, B.A. (2011), "Study of Stall Delay over a Generic Airfoil using Synthetic Jet Actuator", 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, *AIAA 2011-943*.

Ekaterinaris, J.A. (2003),"Active flow control of wing separated flow", ASME FEDSM'03 Joint Fluids Engineering Conference, Honolulu, Hawai, USA, July 6–10.

Gad-el Hak, M. (2000), "Flow Control: Passive, Active and Reactive Flow Management", Cambridge University Press.

Gallas, Q., Holman, R., Nishida, T., Carrol, B., Sheplak, M. and Cattafesta, L. (2003), "Lumped Element Modeling of Piezoelectric- Driven Synthetic Jet Actuators," *AIAA Journal*, Vol. 41, No. 2. 240-247

Gallas, Q. (2005), "On The Modeling And Design Of Zero-Net Mass Flux Actuators", PhD Thesis, Mechanical and Aerospace Engineering, University of Florida.

Geissler, W., Sobieczky, H., and Trenker, M. (2000). "New Rotor Airfoil Design Procedure for Unsteady Flow Control". Duetches Zentrum für Luft-und

Raumfahrt e.V., Institut für Strömungsmechanik, Bunsenstr. 10 D-37073 Göttingen, Germany.

Geissler, W., and Trenker, M. (2002). "Numerical Investigation of Dynamic Stall Control by a Nose-Drooping Device". Presented at the American Helicopter Society Aerodynamics, Acoustics, and Test and Evaluation Technical Specialist Meeting.

Gilarranz, J. and Rediniotis, O. (2001), "Compact, High- Power Synthetic Jet Actuators for Flow Separation Control", *AIAA 2001-0737*.

Gilarranz, J., Traub L. and Rediniotis, O. (2005), "A New Class of Synthetic Jet Actuators - Part II: Application to Flow Separation Control", *Journal of Fluids Engineering*, Vol. 127, pp. 377-387.

Glezer, et al. (1998), "Synthetic Jet Actuator and Application Thereof", United States Patent. 5,758,823

Gomes, L.D., Crowther, W.J. and Wood, N.J. (2006), "Towards a practical piezoceramic diaphragm based synthetic jet actuator for high subsonic applications – effect of chamber and orifice depth on actuator peak velocity" 3rd AIAA Flow Control Conference 5 - 8 June, San Francisco, California. *AIAA 2006-2859*

Greenblatt, D. and Wygnanski, I. (2000), "The control of flow separation by period excitation", *Progress Aerospace Science* 2000;36(7):487–545.

Greenblatt, D. and Wygnanski, I. (2001), "Dynamic Stall Control by Periodic Excitation, Part 1: NACA 0015 Parametric Study", *Journal of Aircraft*, Vol.38, No.3, pp 430-438.

Gregory, J.W., Ruotolo, J.C., Byerley, A.R., and McLaughlin, T.E. (2007), "Switching Behavior of a Plasma-Fluidic Actuator," 45th AIAA Aerospace Sciences Meeting & Exhibit (*AIAA 2007-0785*), Reno, NV.

Guarino, J.R. and Manno, V.P., (2001),"Characterization of a Laminar Jet Impingement Cooling in Portable Computer Applications", 17th IEEE Semi-Therm. Symposium.

Guy, Y., McLaughlin, T. and Morrow, J. (2001), "Velocity Measurements in a Synthetic Jet", *AIAA 2001- 0118.*

Haack, S.J. (2007), "Flow Control Using Plasma and Synthetic Jet Actuators on Bluff Bodies", Master of Science Thesis, University of Maryland.

Hassan, A., Straub, F. and Charles, B. (1997), "Effects of surface blowing/suction on the aerodynamics of helicopter rotor blade-vortex interactions– a numerical simulation", *Journal America Helicopter* Soc. 42 , 182–194.

Hassan, A. and Munts, E., (2000), “Transverse and Near Tangent Synthetic Jets for Aerodynamic Flow Control”, *AIAA 2000- 4334*.

Hassan, A. (2005), “On the Benefits of Active Flow Control (AFC) for Low Speed Unmanned Rotorcraft/Aircraft”, AHS International Specialist’s Meeting, January.

Haertling, G. (1997), “Rainbow Acuators and Sensors: A New Smart Technology,” Proceeding of the SPIE Smart Structures and Materials, San Diego, Vol 3040, pp 81-92.

Holman, R. Gallas, Q. Carroll, B. and Cattafesta, L. (2003), “Interaction of Adjacent Synthetic Jets in an Airfoil Separation Control Application”, *AIAA paper 2003-3709*

Holman, R., Utturkar, Y., Mittal, R., Smith, B.L. and Cattafesta, L. (2005), “Formation Criterion for Synthetic Jets”, *AIAA Journal,* 0001-1452 vol.43 no.10 (2110-2116).

Huang, J., Corke, T. C., and Thomas, F. O. (2003) “Plasma actuators for separation control of low pressure turbine blades.” *AIAA Paper 2003-1027*.

Hui T., Pramod S., Yingying Z., Jiaxing D. and Yanhua W., (2014),”On the use of synthetic jet actuator arrays for active flow separation control” *Experimental Thermal and Fluid Science* , 57; 1–10

Idogaki, T., Tominaga, T., Senda, K., Ohya, N. and Hattori, T. (1996), "Bending and expanding motion actuators", *Sensors and Actuators A*, Vol 54, pp 760-764.

Jabbal, M. and Zhong, S. (2008), “The near wall effect of synthetic jets in a boundary layer”, *International Journal of Heat and Fluid Flow 29* (2008), page 119–130

Jabbal, M. (2012), “Development of Design Methodology for Synthetic Jet Actuator Array for Flow Separation Control Applications”, 6th AIAA Flow Control Conference 25 - 28 June, New Orleans, Louisiana. *AIAA 2012-3242*

Jebakumar, S.K. (2009), “Aircraft Performance Improvements-A Practical Approach”, DRDO Science Spectrum, March 2009, pp. 4-11

Jenkins L., Althoff Gorton S. and Anders S. (2002), “Flow Control Device Evaluation for an Internal Flow with an Adverse Pressure Gradient”, *AIAA 2002-0266*.

Jordan, L., Ounaies, Z., Tripp, J. and Tcheng, P. (2000), ”Electrical properties and power considerations of a piezoelectric actuator”, NASA/CR-2000-209861, ICASE Report No. 2000-8.

Joshua S., Yen Y.and Ahmed N.A. (2013), "Role of Synthetic Jet Frequency & Orientation in Dynamic Stall Vorticity Creation" , 43rd AIAA Fluid Dynamics Conference & Exhibit Flow Control, June 24-27 San Diego, CA, *AIAA 2013-3165.*

Kevin, B., Philip and Rhett J. (2003), "Flow Control of a NACA 0015 Airfoil Using a Chord-wise Array of Synthetic Jets", *AIAA 2003-0061*.

Kim, K. (2005), "Feedback Control of Flow Separation Using Synthetic Jets", PhD Thesis, Texas A&M University

Kral, L.D., Donovan, J.F., Cain, A.B. and Cary, A.W. (1997), "Numerical simulation of synthetic jet actuators", *AIAA 1997-1824*, 4th Shear Flow Control Conference, Snowmass Village, USA.

Koopmans E. and Hoeijmakers H.W.M. (2014), "Experimental Research on Flow Separation Control Using Synthetic Jet Actuators", 29th Congress of the International Council of the Aeronautical Sciences (ICAS), St. Petersburg, Russia, Sept. 7-12.

Lalande, F., Chaudhry, Z., and Rogers, C., (1995),"A Simplified Geometrically Nonlinear Approach to the Analysis of the Moonie Actuator," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol 42 No.1.

Lee, C.Y., and Goldstein, D.B. (2001), "DNS of Microjets for Turbulent Boundary Layer Control", *AIAA 2001-1013.*

Lee, C.Y and Goldstein, D.B. (2002), "Two-Dimensional Synthetic Jet Simulation", *AIAA Journal*, Vol. 40, No.3, pp 510-516, 2002.

Lee, C., Ha, Q.P., Hong, G. and Mallinson, S.(2003), "A piezoelectrically actuated micro synthetic jet for active flow control, *Sensors and Actuators",* A 108, 168-174.

Lee, S.J. and Jang, Y.G. (2005), "Control of flow around a NACA 0012 airfoil with a micro-riblet film", *J. Fluids Struct.* **20**, 659–672.

Lin C.Y., Bai C.J. and Hsiao F.B (2014), "An Investigation on Fundamental Characteristics of Excited Synthetic Jet Actuator Under Cavity and Diaphragm Resonances", 37th National Conference on Theoretical and Applied Mechanics (37th NCTAM) & The 1st International Conference on Mechanics, Procedia Engineering 79, 35 – 44

Lorber, P., McCormick, D., Anderson, T., Wake, B., MacMartin, D., Pollack, M., Corke, T. and Bruer, K. (2000). "Rotorcraft Retreating Blade Stall Control". *AIAA 2000-2475.*

Magill, J., Bachmann, M., Rixon, G., and McManus, K. (2001). "Dynamic Stall Control Using a Model-Based Observer". *AIAA 2001-0251.*

Mane, P., Mossi, K. and Bryant, R. (2005), "Synthetic jets with piezoelectric diaphragms", *Smart Structures and Materials*, Active Materials: Behavior and Mechanics, Proceedings of SPIE Vol. 5761, doi: 10.1117/12.599584

Manu, J., Bhalchandra, P. and Amit A. (2011), "A numerical investigation of effects of cavity and orifice parameters on the characteristics of a synthetic jet flow", *Journal of Sensors and Actuators A* : *Physical 165* (2011) 351–366

Martiqua, L. (2004), "Plasma actuators for separation control on stationary and oscillating airfoils", PhD Thesis, Aerospace and Mechanical Engineering, University of Notre Dame, Indiana.

Matlis, E.H., (2004), "Controlled experiments on instabilities and transition to turbulence on a sharp cone at Mach 3.5", PhD Thesis, University of Notre Dame.

McCormick, D. (2000), "Boundary Layer Separation Control with Directed Synthetic Jets", *AIAA Paper 2000-0519*.

McCormick, D.C, Lozyniak , S. A., MacMartin, D. G., and Lorber, P. F. (2001), "Compact, High-Power Boundary Layer Separation Control Actuation Development". Proceedings of ASME FEDSM'01. Paper No. 18279.

Miller A.C. (2004), "Flow Control Via Synthetic Jet Actuation", Master of Science Thesis, Texas A&M University.

Mittal, R., Rampunggoon, P. and Udaykumar, H. (2001), "Interaction of a synthetic jet with a flat plate boundary layer", *AIAA paper 2001-2773.*

Montazer E., Mirzaei1 M., Salami E., Ward T. A., Romli F. I. and Kazi S. N., (2016), "Optimization of a synthetic jet actuator for flow control around an airfoil", AEROTECH VI - Materials Science and Engineering 152, doi:10.1088/1757-899X/152/1/012023

Morel-Fatio, S., Pines, D. and Kiddy, J. (2003), "UAV Performance Enhancements with Piezoelectric Synthetic Jet Actuators", *AIAA paper 2003-6932*

Mossi, K., Selby, G., and Bryant, R. (1998), "Thin-Layer Composite Unimorph Ferroelectric Driver and Sensor Properties", Materials Letters, Vol. 35, pp 39–49.

Mossi, K., Bishop, R. (1999), "Characterization of Different Types of High Performance Thunder Actuators," Proceedings SPIE Smart Structures Materials, San Diego, Vol. 3675, pp 738-743.

Mossi, K., Ounaies, Z., Smith, R., and Ball, B. (2003), "Pre-stressed Curved Actuators: Characterization and Modeling of their Piezoelectric Behavior", SPIE 5053-54.

Mossi, K. and Bryant, R. (2004a), "Synthetic jets for piezoelectric actuators", Materials Research Society, pp 407–412.

Mossi, K. and Bryant, R. (2004b),"Characterization of piezoelectric actuators for flow control over a wing", Actuator 2004, pp 181-185.

Mossi, K., Mane, P. and Bryant, R. (2005), "Velocity Profiles of Synthetic Jets using Piezoelectric Circular Actuators" 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, Texas, *AIAA 2005-2341*

Mueller, T. J. and Burns, T. F. (1982), "Experimental Studies of the Eppler 61 Airfoil at Low Reynolds Numbers," *AIAA Paper 82-0345*.

Muller, T.J. (2001), "Flow Structure and Performance of Axisymmetric Synthetic Jets," *AIAA Paper 2001-1008*.

Ounaies, Z., Mossi, K., Smith, R. and Bernd, J. (2001), "Low-Field and High-Field Characterization of Thunder Actuators," Proceedings SPIE Smart Structures and Materials, San Diego, Vol 4333, pp 399-407.

Parekh, D.E. and Glezer, A. (2000), "AVIA: Adaptive Virtual Aerosurface", *AIAA paper 2000-2474.*

Post, M. and Corke, T., (2003) "Airfoil leading-edge separation control using plasma actuators." *Bulletin of the American Physical Society Division of Fluid Dynamics*, Vol. 48.

Pragati, P. and Baskar, S. (2015), "Aerodynamic Analysis of Blended Winglet for Low Speed Aircraft", Proceedings of the World Congress on Engineering (WCE 2015), Vol II London, U.K.

Rathnasingham, R. and Breuer, K.S. (1997), "Coupled Fluid–Structural Characteristics of Actuators for Flow Control", *AIAA Journal*, Vol. 35, No. 5.

Rae, W. H., Jr. and Pope, A. (1984), "Low-Speed Wind Tunnel Testing", 2nd ed.,Wiley, New York, pp. 176, 344–444.

Régis, D. and Michel V. (2006), "Simulation and optimization of stall control for an airfoil with a synthetic jet", *Aerospace Science and Technology 10* (2006) 279–287.

Rehman, A. and Kontis, K. (2006), "Synthetic Jet Control Effectivness on Stationary and Pitching Airfoils", *Journal of Aicraft*, Vol. 43, No. 6 pp 1782-1789

Rizzetta, D.P., Visbal, M.R and Stanek, M.J. (1999), "Numerical Investigation of Synthetic Jet Flowfields". *AIAA Journal*, Vol. 37, No. 8, pp 919-927.

Robert, J.P. (1992), "Drag reduction: an industrial challenge - Special Course on Skin Friction Drag Reduction", AGARD- R-786, Paper No.2.

Santos, L.A., Reis, M.L., Mello, O.A. and Mezzalira, L.G. (2006), “Propagation of Uncertainties in the Calibration Curve Fitting of Single Normal Hot-wire Anemometry Probes”, XVIII IMEKO World Congress, Metrology for a Sustainable Development, September, 17 – 22, Rio de Janeiro, Brazil.

Seifert, A., Bachar, T., Koss, D., Shepshelovich, M. and Wygnanski, I. (1993), “Oscillatory Blowing - A Tool to delay Boundary Layer Separation”, *AIAA Journal*, 31(11), pp. 2052-2060.

Seifert, A., Darabi, A. and Wygnanski, I. (1996), “Delay of airfoil stall by periodic excitation”, *AIAA Journal of Aircraft*, 33 (4), 691-699.

Seifert, A. and Pack, L. (1999), “Oscillatory Flow of Separation at High Reynolds Numbers”, *AIAA Journal*, Vol. 37, No. 9, September.

Seifert, A. and Pack, L.G. (2000), “Sweep and Compressibility Effects on Active Separation Control at High Reynolds Numbers”, *AIAA Paper 2000-0410.*

Seifert, A. and Pack, L. (2002) Active Flow Separation Control on Wall Mounted Hump at High Reynolds Numbers, *AIAA Journal*, Vol. 40, No. 7, pp. 1363-1372.

Schwartz, R., W., Narayanan, M., (2002), “Development of high performance stress-biased actuators through the incorporation of mechanical pre-loads,” *Sensors and Actuators A*, Vol 101, pp 322-331.

Scott, J. (2005), “Wing Vortex Devices”, aerospaceweb.org, http://www.aerospaceweb.org/question/aerodynamics/q0228.shtml

Sharma, R.N. (2006), “An Analytical Model for Synthetic Jet Actuation”, 3rd AIAA Flow Control Conference, San Francisco, California, *AIAA 2006-3035*

Sharma, D.M. and Poddar, K. (2009), “Effect of Reduce Frequency and Reynolds Number on Hysteresis Behavior of Flow Past an Oscillating Airfoil”, 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition 5 - 8 January Orlando, Florida, *AIAA 2009-330*

Shaw, L., Smith, B. and Saddoughi, S. (2006), “Full Scale Flight Demonstration of Active Flow Control of a Pod Wake”, *AIAA paper 2006-3183*.

Sheldahl, R. E., and Klimas, P. C. (1981), “Aerodynamic Characteristics of Seven Airfoil Sections Through 180 Degrees Angle of Attack,” Sandia National Laboratories, Albuquerque, NM,

Shih, W., Y., Shih, W., H., and Aksay, I., A., (1997), "Scaling Analysis for the Axial Displacement and Pressure of Flextensional Transducers," *Journal of American Ceramic Society*, Vol 80 No5, pp1073-1078.

Shuster, J.M., and Smith, D.R. (2004), “A Study of the Formation and Scaling of a Synthetic Jet”, *AIAA Paper 2004-0090.*

Smith, B. and Glezer, A. (1997), "Vectoring and Small Scale Motions Effected in Free Shear Flows Using Synthetic Jet Actuators", *AIAA Paper 97-0213*.

Smith, B and Glezer, A.(1998), "The formation and Evolution of Synthetic Jets", *Physics of Fluids*, 10 (9), 2281-2297.

Smith D., Amitay M. and Glezer A. (1998), "Modification of Lifting Body Aerodynamics using Synthetic Jet Actuators", *AIAA 98-0209*.

Smith, B.L., (1999a),"Synthetic Jets and their Interaction with Adjacent Jets," PhD Dissertation, Mechanical Engineering Dept., Georgia Institute of Technology, Atlanta.

Smith, B., Trautman, M. and Glezer, A. (1999b), "Controlled Interactions of Adjacent Synthetic Jets", *AIAA 99-0669*.

Song, L., Sun, Y., Liu, Y., Ming, L.,Wang, S. and Wang, D. (2013), "Research Progress and Application in Aeronautics of Flow Control Technology for Increasing Lift and Reducing Drag", Proceedings of the 2nd International Conference on Computer Science and Electronics Engineering (ICCSEE 2013).

Szodruch, J. (1991), "Viscous drag reduction on transport aircraft", *AIAA paper 91-0685*.

Tang, H. and Zhong, S. (2005), "The Effect of Actuator Geometry on the Performance of Synthetic Jets". *CEAS/KATnet Conference on Key Aerodynamic Technologies*, Bremen, Germany.

Traub, L., Miller, A. and Rediniotis, O. (2004), "Effects of Synthetic Jet Actuation on a Ramping NACA 0015 Airfoil", *Journal of Aircraft*, Vol. 41, No. 5.

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

Tuck, A. and Soria, J. (2006), "Dynamic-Active Flow Control - Phase I", Laboratory for Turbulence Research in Aerospace and Combustion Department of Mechanical Engineering, Monash University, Melbourne, Australia, Aoard Project Id: Fa5209-05-T-0435

Tuck, A. and Soria J. (2008), "Separation control on a NACA 0015 airfoil using a 2D micro ZNMF jet", *Aircraft Engineering and Aerospace Technology*, Vol. 80 Iss: 2 pp. 175 – 180

Tuncer, I. and Sankar, L. N. (1994). "Unsteady Aerodynamic Characteristics of a Dual-Element Airfoil," *Journal of Aircraft*, 31(3).

Ugrina, S. and Flatau, A.B. (2004), "Investigation of synthetic jet actuator design parameters", Proceedings Paper , SPIE 5390, Smart Structures and Materials 2004: Smart Structures and Integrated Systems, Vol. 5390.

Ugrina, S. (2007), Experimental Analysis and Analytical Modelling of Synthetic Jet Cross Flow Interactions, PhD Thesis, Department of Aerospace Engineering, University of Maryland.

Utturkar, Y., Mittal, R., Rampunggoon, P., and Cattafesta, L. (2002), "Sensitivity of Synthetic Jets to the Design of the Jet Cavity," *AIAA Paper 2002-0124*.

Utturkar, Y., Holman, R., Mittal, R., Carroll, B., Sheplak, M, and Cattafesta, L. (2003), "A Jet Formation Criterion for Synthetic Jet Actuators," *AIAA Paper 2003-0636.*

Vargas, Y.L., Finley, T.J., Mohseni, K. and Hertzberg, J. (2006), "Flow Characterization of a Synthetic Jet"' 44th AIAA Aerospace Sciences Meeting and Exhibit 9 - 12 January, Reno, Nevada. *AIAA 2006-1422*

Viswanath, P. R. (2002), "Aircraft viscous drag reduction using riblets", *Prog. Aerosp. Sci.* 38, 571–600. (doi:10.1016/S0376-0421(02)00048-9)

Walsh, M. J. and Lindemann, A. M. (1984), "Optimization and application of riblets for turbulent drag reduction", *AIAA paper 84-0347*.

Wang, Q., M., Zhang, Q., Xu, B., Liu, R., Cross, L., E., (1999), "Nonlinear piezoelectric behavior of ceramic bending mode actuators under strong electric fields," *Journal of Applied Physics*, Vol 86 No. 6, pp 3352-3360.

Wood, N.J., Sadri, A.M., and Crook, A. (2000), "Control of turbulent flow separation by synthetic jets", *AIAA 2000-4331*, 18th AIAA Applied Aerodynamics Conference, Denver, USA.

Wu, J., Lu, X., Denney, A. and Fan, M. (1997), "Post-stall lift enhancement on an airfoil by local unsteady control, part I. Lift, drag and pressure characteristics", *AIAA paper 97-2063.*

Wu, J., Lu, X., Denny, A., Fan, M. and Wu, J., (1998), "Post-stall flow control on an airfoil by local unsteady forcing", *Journal of Fluid Mechanics*, Vol. 371, pp. 21-58.

Wu, K. and Breuer, K. (2003), "Dynamics of Synthetic Jet Actuator Arrays for Flow Control", *AIAA Paper 2003-4257*.

Wygnanski, I. (1997), "Boundary Layer and Flow Control by Periodic Addition of Momentum", *AIAA Paper 97-2117.*

Yang, A.S. (2009), "Design analysis of a piezoelectrically driven synthetic jet actuator", *Journal of Smart Materials and Structures*, 18-125004 (12pp)

Zhao G., Zhao Q., Yunsong G. and Chen X., (2016), "Experimental investigations for parametric effects of dual synthetic jets on delaying stall of a thick airfoil", Chinese Journal of Aeronautics, 29(2): 346–357

Zifeng Y., Hirofumi I., Mathew M. and Hui H., (2008),"An Experimental Investigation on Aerodynamic Hysteresis of a Low-Reynolds Number Airfoil", 46th AIAA Aerospace Sciences Meeting and Exhibit Jan 7 – 10, Reno, Nevada, *AIAA-2008-0315*.

Zhou, J. (2010), "Numerical Investigation of the Behaviour of Circular Synthetic Jets for Effective Flow Separation Control", Doctor of Philosophy Thesis, University of Manchester.

Zyga, L. (2012), "Scientists discover second purpose for vortex generators", Phys.org http://phys.org/news/2012-09-scientists-purpose-vortex.html