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)

v - 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.

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