Faculty of Mechanical Engineering

EXPERIMENTAL STUDY OF FLOW AROUND AIRFOIL USING DIELECTRIC BARRIER DISCHARGE PLASMA ACTUATOR

Farah Ayiesya binti Zainuddin

Master of Science in Mechanical Engineering

2019

EXPERIMENTAL STUDY OF FLOW AROUND AIRFOIL USING DIELECTRIC BARRIER DISCHARGE PLASMA ACTUATOR

FARAH AYIESYA BINTI ZAINUDDIN

A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
in Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled “Experimental Study of Flow Around Airfoil Using Dielectric Barrier Discharge Plasma Actuator” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …………………………..

Name : …………………………..

Date : …………………………..

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : …………………………..
Supervisor Name : …………………………..
Date : …………………………..

DEDICATION

In the name of Allah, the Most Gracious and the Most Merciful

I dedicate this work to:

My parents,

Zainuddin bin Mohd Noh and Maznah binti Yusoff

My siblings,

Mentors who always give support and encouragement,

Dr. Nazri bin Md Daud, Dr. Cheng See Yuan, En Muhammad Amir Asyraf bin Abdul Kadir

ABSTRACT

Dielectric barrier discharge (DBD) plasma actuator has become a popular device in the aerodynamic flow control applications. The number of application of DBD plasma actuator increases due to its special features such as no moving parts, quick response and extremely low mass. For example, plasma actuators have been applied for flow control on airfoil, flow control around circular cylinders, delaying separation on turbine blades and improving the aerodynamic performance on cars. This study deals with the enhancement of aerodynamic performance on NACA 0015 airfoil when a DBD plasma actuator is mounted near the leading edge by using steady actuation method. Flow visualization test, lift and drag force test and pressure distribution test on upper surface airfoil test were conducted to investigate the effectiveness of DBD plasma actuator. A study on a NACA 0015 is performed to improve its aerodynamic performance particularly focused on the flow distribution visualized over an airfoil body, the evaluation and correlation of lift (C_L), drag (C_D) and pressure coefficient (C_P). The results were compared between the base case (DBD plasma actuator OFF) and actuation case (DBD plasma actuator ON). Experimental works were performed in the wind tunnel test section at Reynolds number (Re) approximately 0.63×10^5 to 2.52×10^5 with external airflow 5 m/s for flow visualization test while 15 m/s and 20 m/s for lift and drag force test. The DBD plasma actuator was installed on NACA 0015 airfoil with 190 mm chord length and 260 mm span length at $x/c = 0.025$, where x is the vertical distance measured from leading edge and c was the chord length. The DBD plasma actuator consists of two copper tape electrodes with 10 mm width and 50 μm thick that arranged parallel with 1 mm overlap. For the dielectric material, a Kapton film with 100 μm thickness was attached between these electrodes. A high voltage AC current was used where the output of the circuit can reach up until 6 kV with frequency 16 kHz. The result showed that actuation case was able to increase the aerodynamic performance of an airfoil by increasing lift coefficient about 22 % for 15 m/s and 49 % for 20 m/s, reducing the drag coefficient about 19 % for 15 m/s and 49 % for 20 m/s and recovering the pressure distribution about 1 %. These results were supported by flow visualization result which conducted at angles of attack $\alpha = 15°$ to $\alpha = 18°$. These angles of attack are the important phases for airfoil during stall control condition ($\alpha = 15°$), stall point ($\alpha = 16°$) and high angle of attack ($\alpha = 17°$ and $18°$). It is noticed that the actuation case results avoids a massive flow detachment from leading edge by producing strong vortices from plasma generation. The strong vortices flow near the airfoil surface and as a result, the C_L for actuation case may increase. Therefore, the DBD plasma actuator became a better device to replace other mechanical devices especially in aeronautical field.

ABSTRAK

Dielektrik halangan pelepasan (DBD) penggerak plasma telah menjadi alat yang terkenal dalam aplikasi kawalan aliran aerodinamik. Bilangan penggunaan DBD halangan penggerak plasma bertambah disebabkan oleh ciri-ciri khasnya seperti tiada bahagian yang bergerak, cepat bertindak balas dan mempunyai jisim yang sangat rendah. Contohnya, penggerak plasma telah digunakan untuk mengawal aliran pada kerajang udara, mengawal aliran di sekitar silinder bulat, melambatkan pemisahan pada bilah turbin dan meningkatkan prestasi aerodinamik pada kereta. Kajian ini berkait dengan peningkatan prestasi aerodinamik ke atas NACA 0015 kerajang udara apabila DBD halangan penggerak plasma dipasang pada bahagian yang berdekatan pinggiran hadapan kerajang udara dengan menggunakan langkah penjanaan plasma tetap. Ujian aliran gambar, ujian daya angkat dan seret dan ujian pengedaran tekanan pada permukaan atas kerajang udara dilakukan untuk mengkaji keberkesanan DBD halangan penggerak plasma. Kajian pada kerajang udara NACA 0015 dilakukan dengan tujuan untuk meningkatkan prestasi aerodinamik dengan tumpuan khusus pada penilaian dan hubung kait pada pekali angkat, pekali seretan dan pekali tekanan. Selain itu, gambar aliran pada badan kerajang udara dapat dijelaskan Hasilnya telah dibandingkan antara kes asas (DBD halangan penggerak plasma dimatikan) dan kes penjanaan plasma (DBD halangan penggerak plasma dihidupkan). Kerja-kerja ujikaji dilakukan pada nombor Reynolds (Re) anggaran 0.63×10^5 sehingga 2.52×10^5 dengan aliran udara luaran 5 m/s untuk ujian aliran gambar kemudian 15 m/s dan 20 m/s untuk ujian daya angkat dan seret. DBD halangan penggerak plasma telah dipasang pada kerajang udara NACA 0015 dengan panjang perentas 190 mm dan lebar 260 mm pada $x/c = 0.025$, di mana x adalah jarak tegak yang diukur dari pinggir depan dan c ialah panjang perentas. DBD penggerak plasma terdiri daripada dua elektrod pita tembaga dengan lebar 10 mm dan tebal 50 μm yang disusun selari dengan jarak 1 mm bertindih. Untuk bahan dielektrik, filem Kapton dengan 100 μm tebal dilekatkan diantara elektrod-elektrod ini. Arus AC voltan tinggi digunakan di mana output litar boleh mencapai sehingga 6 kV dengan kekerapan 16 kHz. Hasilnya menunjukkan bahawa kes-kes penjanaan plasma dapat meningkatkan prestasi aerodinamik kerajang udara dengan peningkatan pekali angkat kira-kira 22 % untuk 15 m/s dan 49 % untuk 20 m/s, mengurangkan pekali seret kira-kira 19 % untuk 15 m/s dan 49 % untuk 20 m/s, memulihkan pengagihan tekanan pada purata 1 %. Pekali telah disokong oleh keputusan gambar aliran pada 15° sehingga 18°. Sudut-sudut serang merupakan fasa yang penting untuk kerajang udara semasa pengawalan keadaan tegun ($\alpha = 15°$), titik tegun ($\alpha = 16°$) dan sudut serang yang tinggi ($\alpha = 17°$ dan $18°$). Keputusan kes penjanaan plasma menunjukkan pemisahan aliran yang besar dapat dielakkan dari pinggir hadapan dengan penghasilan pusaran yang kuat terhasil daripada pembentukan plasma. Pusaran kuat mengalir menghampiri permukaan kerajang udara dan mengakibatkan peningkatan pekali angkat semasa penjanaan plasma.

ACKNOWLEDGEMENTS

First and foremost, I thank Allah s.w.t, the Almighty God for His mercy and grace in enabling me to complete this thesis work. I would like to take this opportunity to express my sincere acknowledgement to my supervisors Dr. Nazri bin Md Daud and Dr. Cheng See Yuan from the Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for their essential supervision, support and encouragement towards the completion of this thesis. I would like to extend my appreciation to Assoc. Prof. Dr. Zolkafle bin Buntat from Institute of High Voltage and High Current, Universiti Teknologi Malaysia (UTM), Johor for his suggestions and support to successfully complete this research.

Special thanks to the Kementerian Pengajian Tinggi (KPT) under the funding of Research Acculturation Grant Scheme (RAGS), Faculty Mechanical Engineering and Centre of Advanced Research on Energy Universiti Teknikal Malaysia Melaka (UTeM) (RAGS/1/2015/TK0/FKM/03/B00102) for financial sponsors, facilities and knowledge during this research.

I would also like to express my greatest gratitude to technician team from Faculty Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), especially to Mr. Faizal bin Jaafar, Mr. Asjufri bin Muhajir, not forgetting to Aero Laboratory and Fluid Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM) team, especially Mr. Abd Basid bin Abd Rahman and Mr. Sahlan bin Sadiron for the technical support and ideas given during collected experiment. Finally, I would like to make an affectionate acknowledgement to my parents, my siblings, all my colleagues and friends who had helped and supported me during my research studies directly or indirectly.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AC - Alternating Current
AOA (α) - Angle of Attack
DBD - Dielectric Barrier Discharge
DC - Direct Current
EHD - Electrohydrodynamic
FKPS - Flow Kinetic Pressure Scanner
MAV - Micro Air Vehicle
MEE - Multiple encapsulated electrodes
MEMS - Microelectromechanical Systems
N - Newton
NACA - National Advisory Committee Aeronautics
PCC - Phantom Camera Control
PIV - Particle Image Velocimetry
PMMA - Polymethyl Methacrylate
PMT - Photomultiplier-Tube
SBDB - Single Dielectric Barrier Discharge
USB - Universal Serial Bus

LIST OF SYMBOLS

A - Area of the object

AP - Actual pressure

α - Angle of attack

β - Burst ratio/ Duty cycle

c - Chord length

C_L - Lift coefficient

C_D - Drag coefficient

C_L/ C_D - Aerodynamic efficiency

C_P - Pressure coefficient

d_D - Debye length

d - Dielectric thickness

D - Drag force

D_O - Indicated drag force

ε_r - Dielectric constant

ε_0 - Permittivity of air

E - Electric field /Dielectric strength

E_* - Electric field

F_{actual} - Actual force

$F_{indicated}$ - Indicated force

F_b - Body force

f_b^* - Body force per volume

F_β - Burst frequency

F^+ - Frequency

h - Height

IF - Indicated force

IP - Indicated pressure

L - Length/ Lift force

ρ - Mass density / Fluid density

p @ P_i	-	Pressure at location ports on the surface
p_o	-	Static pressure of the freestream
p_∞	-	Pressure at some distance from the section
P_1	-	Pressure distribution for laminar stall start
P_2	-	Pressure distribution for turbulent stall start
q_v	-	Ionized components
S_1	-	Point laminar separation start and reattachment
S_2	-	Point of turbulent separation start
SP	-	Static pressure
T	-	Period of ON cycle
TF	-	Tare force/ Reading at wind velocity
TP	-	Tare pressure
$T_{control}$	-	Temporal duration of actuation
T_{signal}	-	Period of one burst cycle
t -	-	Time
μ	-	Fluid viscosity
v	-	Kinematic viscosity
RF	-	Recorded force/ Reading from indicator with wind velocity
RP	-	Recorded pressure
Re	-	Reynolds number
U	-	Velocity
U_o	-	Free stream velocity
V	-	Resistance drag/ Upstream wind velocity
x	-	Vertical distance from leading edge
X	-	Distance of reference mark on the model holder
X_A	-	Actual distance
X_S	-	Indicated distance
φ	-	Electric potential

LIST OF PUBLICATIONS

Zainuddin, F.A. and Daud, N.M., 2018. A Review on Dielectric Barrier Discharge (DBD) Plasma Actuator in Aeronautics Applications. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *48*(2), pp. 125-132.

Zainuddin, F.A, Daud, N.M., Mat, S. and Buntat, Z., 2018. Experimental study on flow around airfoil by using dielectric barrier discharge (DBD) plasma actuator. *ARPN Journal of Engineering and Applied Sciences*, 13(7), pp.2400-2407.

Zainuddin, F.A., Daud, N.M. and Ghani, A.F.A., 2018. Experimental study of flow around airfoil at high angle of attack by using DBD plasma actuator. *Proceedings of Mechanical Engineering Research Day 2018*, *2018*, pp.262-263.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Basically, any process or mechanism through the boundary layer that causes a fluid flow to behave differently is called as the flow control mechanism. The flow control is possible to control or the formations of transition boundary layer, turbulence and flow separation. The advantages of flow control are lift enhancement, drag reduction, increasing heat transfer and reduce the flow noise suppression. There are two methods in flow control such as active and passive methods. Normally, an active method of flow control device requires an energy input in certain amount to introduce into the flow. This method is flexible which can be turned on and off as needed. For the passive flow, it was modified without using external energy. Therefore, during the last decade, the development of active control methods has been emphasized (Johari and McManus, 1997; Amitay and Glezer, 2002; List et al., 2003; Asada et al., 2009; Kotsonis and Ghaemi, 2012; Abdollahzadeh et al., 2018; Dalvand et al., 2018; Nakai et al., 2018).

For a recent year, flow field was focused to microflow control devices which can control a large scale of flow control by adding local momentum. Therefore, Dielectric Barrier Discharge (DBD) plasma actuator is assumed to be a control device that can replace the traditional flow control devices such as vortex generators, slats and flaps. This device has many benefits such as easy structure, rapid response, and low energy consumption (Greenblatt et al., 2012; Fujii, 2014; Nakai et al., 2018). Meanwhile, Moreau

(2007) and Corke et al. (2010) provided a good evaluation of plasma actuator history, basic physics and flow control application with it types.

A DBD plasma actuator includes two electrodes and one dielectric material, where generates plasma via DBD plasma actuator at the vicinity between exposed electrode and embedded electrode when high alternating current (AC) voltage is applied consequently. This generated plasma induces the flow toward the encapsulated electrode from the exposed electrode (Ogawa et al., 2018). Besides, the DBD plasma actuator actually can directly converts electric energy into kinetic energy without involving moving mechanical elements (Moreau, 2007), for instance, plasma actuators have been applied for flow control on airfoil, flow control around circular cylinders, delaying flow separation on turbine blades and improving the aerodynamic performance (Sosa and Artana, 2006; Benard et al., 2008).

Additionally, the easiness by changing the operating mode is also an advantage. By referring Plogmann et al. (2009), the feed-back models with DBD plasma actuator for the separated flow improvement are focused. They proposed that a DBD plasma actuator is applied for unsteady flow conditions such a dynamic stall and the demonstration of the feed-back control to separate flow under dynamic stall condition by DBD plasma actuator using a microphone to measure a noise of the instantaneous of the frequency peak has been done. They assumed that measured peak frequency directly relates to the unstable frequency of the separated shear layer and the actuation with the peak frequency can increase the lift and decrease the drag. Besides, the DBD plasma actuator is more efficient when it acts near to the natural separation vicinity, and that the power consumption can be quite reduced in using a non-stationary actuation (Jolibois et al., 2008).

Plasma actuator is a type of electrical actuator that capable ionizing the flowing air and add localized momentum to the flow through collision process of migrating charged