UNIVERSITI PUTRA MALAYSIA

NUMERICAL AND EXPERIMENTAL STUDY OF LEADING EDGE TUBERCLES WITH VORTEX GENERATORS ON NACA 4415 AIRFOIL

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By

SYED MOHAMMED AMINUDDIN AFTAB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

March 2017

DEDICATION

This thesis is dedicated to my parents and inspiring teachers,

(Mr. S. M. M. Peerzada and Mrs. S. F. N. Sultana)

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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Low Reynolds number flows are associated with the problems of separation bubble. The presence of separation bubble reduces the performance of the airfoil. The most commonly used devices in order to increase the performance in these Reynolds number range are Vortex Generators (VG). Recently studies have shown that implementing humpback whale Tubercle Leading Edge (TLE), also enhance the performance of the airfoil. The objective of the current work is to combine TLE and VG thereby elimination of separation bubble and increase airfoil lift to drag ratio. Initially the flow over NACA 4415 at low Reynolds number (Re) of 120,000 using Computational Fluid Dynamics (CFD) is carried out, and proper methodology for selection of turbulence model for low Re flows is also reported. Five turbulence models, were tested and it was found that γ-Re_θ sst was the best suitable Reynolds Averaged Navier Stokes (RANS) model to capture the flow physics. The main mesh requirements for utilizing γ-Re_θ sst is to maintain the wall y+ <1. Throughout the thesis, structured meshing has been carried out using ICEM CFD. The established turbulence model was used to conduct CFD analysis on two Tubercle Leading Edge (TLE) designs. The designs tested are, 1. Spherical 2. Sinusoidal, the geometry is modeled using CATIA V5R21. A parametric study varying the amplitude of the tubercles is also carried out. The wavelength was kept constant at 0.25c three amplitude variations 0.025c, 0.05c and 0.075c, were modeled for both spherical and sinusoidal tubercles designs. The flow Re was set to 120,000. As the tip effects were neglected, the results are for 2.5D, only the effect of span is taken into consideration. A 3D hex grid was generated around the rectangular domain with a span of 0.5c. The results showed that spherical tubercle with 0.025c amplitude was efficient at 18°AoA, it increased the l/d ratio by 6.25%. Based on these CFD results, a modified NACA 4415 airfoil with spherical TLE was fabricated. Wind tunnel testing was carried out at Re 200,000. The results were compared with previous experimental work on NACA 4415 with straight leading edge. The results of spherical TLE showed an improvement in lift to drag ratio by 67.3% at 0°, 14% at 6°, 17.6% at 12° and the performance decrement at 18° by 3.23%. This proves that spherical TLE do improve the performance but Re number effect is an important aspect which needs to be studied. Finally a CFD analysis combining spherical TLE and VG is studied. This is the novelty of the current research is the combination of TLE and VG. The results showed that the combination enhanced the performance of clean airfoil by 8.9%. TLE and VG combination improved performance by 50% at 12º AoA as compared to merely TLE airfoil. The breakthrough finding was the working mechanism of spherical TLE which appeared similar to sub boundary layer VG. Thus the combination of TLE and VG gives a major boost in enhancing the performance of airfoil working in low Re range.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KAJIAN BERANGKA DAN EKSPERIMEN TUBERKEL PINGGIR DEPAN DENGAN PENGHASIL PUSARAN KE ATAS AEROFIL NACA 4415

Oleh

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Aliran pada nombor Reynolds rendah sering dikaitkan dengan masalah gelembung pemisah. Kehadiran gelembung pemisah mengurangkan prestasi aerofil. Peranti yang sering digunakan untuk meningkatkan prestasi pada julat nombor Reynolds ini ialah penghasil pusaran (VG). Kajian terkini menunjukkan penggunaan tuberkel pinggir depan (TLE) juga dapat meningkatkan kecekapan aerofil. Objektif kajian ini adalah untuk mengabungkan TLE dan VG seterusnya menghapuskan gelembung pemisah dan meningkatkan nisbah angkat kepada seretan aerofil. Pada mulanya, aliran ke atas aerofil NACA 4415 pada nombor Reynolds (Re) 120,000 menggunakan Pengkomputeran Dinamik Bendalir (CFD) dijalankan, dan pemilihan model gelora dilaporkan. Lima model gelora, di uji dan didapati γ-Re_θ SST adalah model Reynolds Purata Navier Stokes (RANS) yang terbaik untuk mengukur aliran fizik. Keperluan utama jejaring untuk menggunakan γ-Re_θ SST adalah dengan mengekalkan nilai dinding y^+ <1. Dalam kajian ini, jejaring berstruktur telah dihasilkan menggunakan ICEM CFD. Model gelora yang ditubuhkan telah digunakan untuk menjalankan analisis CFD pada dua reka bentuk TLE. Reka bentuk yang diuji adalah, 1. Sfera 2. Sinus, geometri dimodelkan menggunakan CATIA V5R21. Satu kajian parametrik dijalankan dengan mengubah amplitud tuberkel. Panjang gelombang ditetapkan pada 0.25c. Tiga variasi amplitud 0.025c, 0.05c dan 0.075c, dimodelkan untuk reka bentuk tuberkel kedua-dua sfera dan sinus. Nombor Re bagi aliran ditetapkan pada 120,000. Disebabkan kesan hujung diabaikan, keputusan adalah untuk 2.5D, hanya kesan rentang diambil kira. Grid segi enam 3D telah dihasilkan sekitar domain segi empat tepat dengan rentang 0.5c. Hasil kajian menunjukkan bahawa tuberkel sfera dengan 0.025c amplitud menghasilkan kecekapan pada 18° AoA, telah meningkatkan nisbah L / D sebanyak 6.25%. Berdasarkan kepada keputusan CFD ini, aerofil NACA4415 yang diubahsuai dengan bentuk sfera TLE telah difabrikasi. Ujian terowong angin telah dijalankan pada Re 200,000. Keputusan ini dibandingkan dengan kerja eksperimen sebelum ini pada NACA 4415 dengan pinggir depan lurus. Keputusan bentuk sfera TLE menunjukkan peningkatan dalam nisbah lif kepada seret sebanyak 67.3% pada 0°, 14% pada 6°, 17.6% pada 12º dan susutan kecekapan pada 18°

sabanyak 3.23%. Ini membuktikan bahawa sfera TLE menghasilkan kecekapan prestasi tetapi kesan nombor Re merupakan aspek penting yang perlu dikaji. Akhirnya analisis CFD yang menggabungkan sfera TLE dan penghasil pusaran (VG) dikaji. Ini adalah sesuatu yang baru bagi penyelidikan semasa, setakat ini gabungan TLE dan VG masih belum pernah dilaporkan. Hasil kajian menunjukkan bahawa kombinasi ini meningkatkan prestasi aerofil bersih sebanyak 8.9%. Gabungan TLE dan VG meningkatkan prestasi sebanyak 50% pada 12° AoA berbanding dengan aerofil TLE. Penemuan utama adalah terhadap mekanisme kerja sfera TLE yang sama dengan sub VG lapisan sempadan. Oleh itu gabungan TLE dan VG memberikan rangsangan utama dalam meningkatkan prestasi aerofil pada Re rendah.

This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

AGI	Airfoil Gust Interaction
AoA	AoA
BL	Boundary Layer
CAA	Computational Aero Acoustic
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Controlled
CTRM	Composite Technology Research Malaysia
DAQ	Data Acquisition
DARC	Data Acquisition Reduction and Control
DDES	Delayed Detached Eddy Simulation
DDLE	Dynamically Deformed Leading Edge
DES	Direct Eddy Simulation
DSM	Dynamic Smagorinsky Model
Gmi	German Malaysian Institute
HAWT	Horizontal Axis Wind Tunnel
HPC	High Performance Computing
IBM	Immersed Boundary Method
ISVR	Institute of Sound and Vibration Research
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulation
LEV	Leading Edge Vortex
MAV	Micro Air Vehicle
MOGA	Multi Objective Generic Algorithm
NACA	National Advisory Commitee for Aeronautics
NASA	National Aeronautics and Space Administration
Open FOAM	Open source Field Operation And Manipulation
PIV	Particle Image Velocimetry
PNLLT	Prandtl's Nonlinear Lifting Line Theory
RANS	Reynolds Averaged Navier Stokes
SA	Spalart Allmaras
SBVG	Sub Boundary Layer Vortex Generator
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SLE	Straight Leading Edge
SMA	Shape Memory Alloys
SPIV	Stereo Particle Image Velocimetry

SST	Shear Stress Transport
SWFS	Solid Works Flow Simulation
TLE	Tubercle Leading Edge
T-S	Tollmien-Schlichting
UAV	Unmanned Aerial Vehicle
VAWT	Vertical Axis Wind Tunnel
VG	Vortex Generators

LIST OF SYMBOLS

2D	Two Dimensional	
3D	Three Dimensional	
A	Amplitude	m
c	Chord	m
C_d	Coefficient of Drag	
C_l	coefficient of Lift	
C_m	Coefficient of Moment	
C_p	Coefficient of Pressure	
d	Distance between VG	m
e	Thickness of the VG	m
G	Generation Term	N/m^3
h	Height of the VG	m
K	Turbulent Kinetic Energy	m^2/s^2
KL	Laminar Kinetic Energy	
L	Length of the VG	m
L/D	Lift to drag ratio	
Re	Reynolds Number	
Re_θ	Transition Reynolds Number	
S	Span	m
S	Source Term	N/m^3
x	Length of the airfoil	m
β	VG orientation angle	deg
γ	Intermittency	
δ	Boundary layer thickness	m
ε	Turbulence Dissipation Rate	m^2/s^3
λ/W	Wavelength	m
ω	Specific Dissipation Rate	1/s

CHAPTER 1

INTRODUCTION

The dream of flying has baffled humanity since earliest times. Greek mythology depicts the flight of Icarus, with wings made of wax, flying towards the sun. The Ancient Egyptian god Khensu had wings and was known as a traveler journeying through the skies. These stories have been a dream for man, inspiring him to achieve the goal of flying. Only at the beginning of the 20^{th} century, this dream was possible. The first human photographed in airplane is Otto Lilienthal, with over 2000 successful glider flights and was the inspiration to the efforts of powered flight by Wright brothers Anderson, (2005). The current goal of the aerospace industry is to develop greener technologies. This can be achieved only by reducing the structural weight, using a highly efficient propulsion system, increasing the aerodynamic efficiency and decreasing the overall drag.

1.1 Flow control

The major areas where flow control is necessary are wings, rudders, fans and turbines. Flow on aerodynamic surfaces has to be attached at a high Angle of Attack (AoA), as this increases operational capability, efficiency, range and endurance Green, (2008).
Aerodynamic flow control is classified into active, passive and hybrid. The active flow control technique is one where actuators and other mechanisms are used. Passive flow control mainly employs devices or modification without involving actuators and complex mechanisms. In hybrid control, both active and passive mechanisms are implemented. The main aim of these devices is to control separation. Figure1.1 shows the interrelation of separation to lift, drag, transition and reattachment. A detailed description of the various flow separation control methods, both active and passive, has been elaborately covered by Gad-el-Hak, (2007).

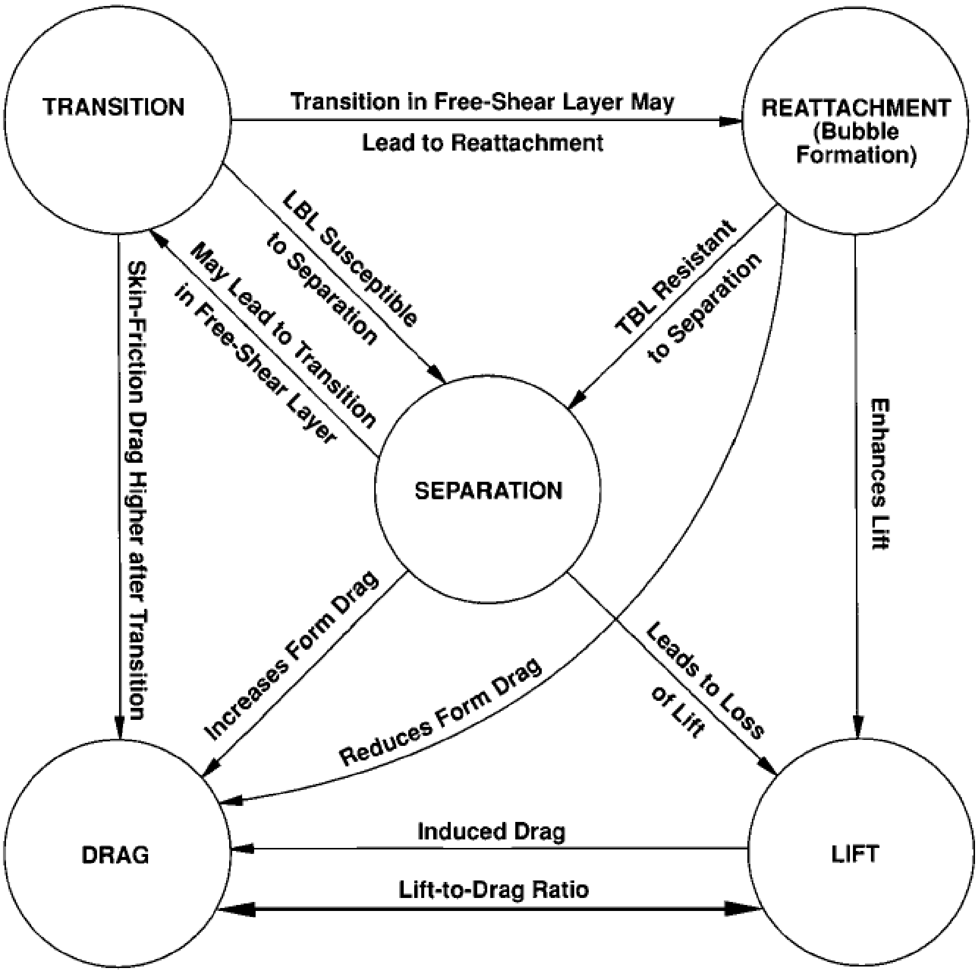

Figure 1.1: Effects of separation Gad-el-Hak, (2007)

1.2 Biomimetics

The study of the structures and functions of biological systems in the design of engineering systems is known as biomimetics. In general, this means imitating nature to solve engineering problems. A detailed review and the in-depth technological applications of various biological systems in relation to engineering has been compiled by Yoseph Bar- Cohen, (2005). Some of the most fascinating bio-mimicking studies, from the aerodynamic perspective, include the flight of owls and seagulls (Collins, 1981; Cranston et al., 2012; Hua et al., 2010; Ito, 2009; Klan et al., 2010; Lilley, 1998). Owls have the ability to approach their prey in total silence, and the flapping sound is damped by leading edge serrations, giving them the ability to control the flow (Collins, 1981; Klan et al., 2010; Lilley, 1998).

Aerodynamic engineers draw inspiration from marine animals. Designing an aircraft skin similar to that of sailfish and swordfish, or implementing riblets inspired by sharks, has been beneficial in overcoming the skin friction drag on aircraft. Bhushan, (2009) summarises various inspirations drawn from nature and their applications as shown in Figure 1.2.

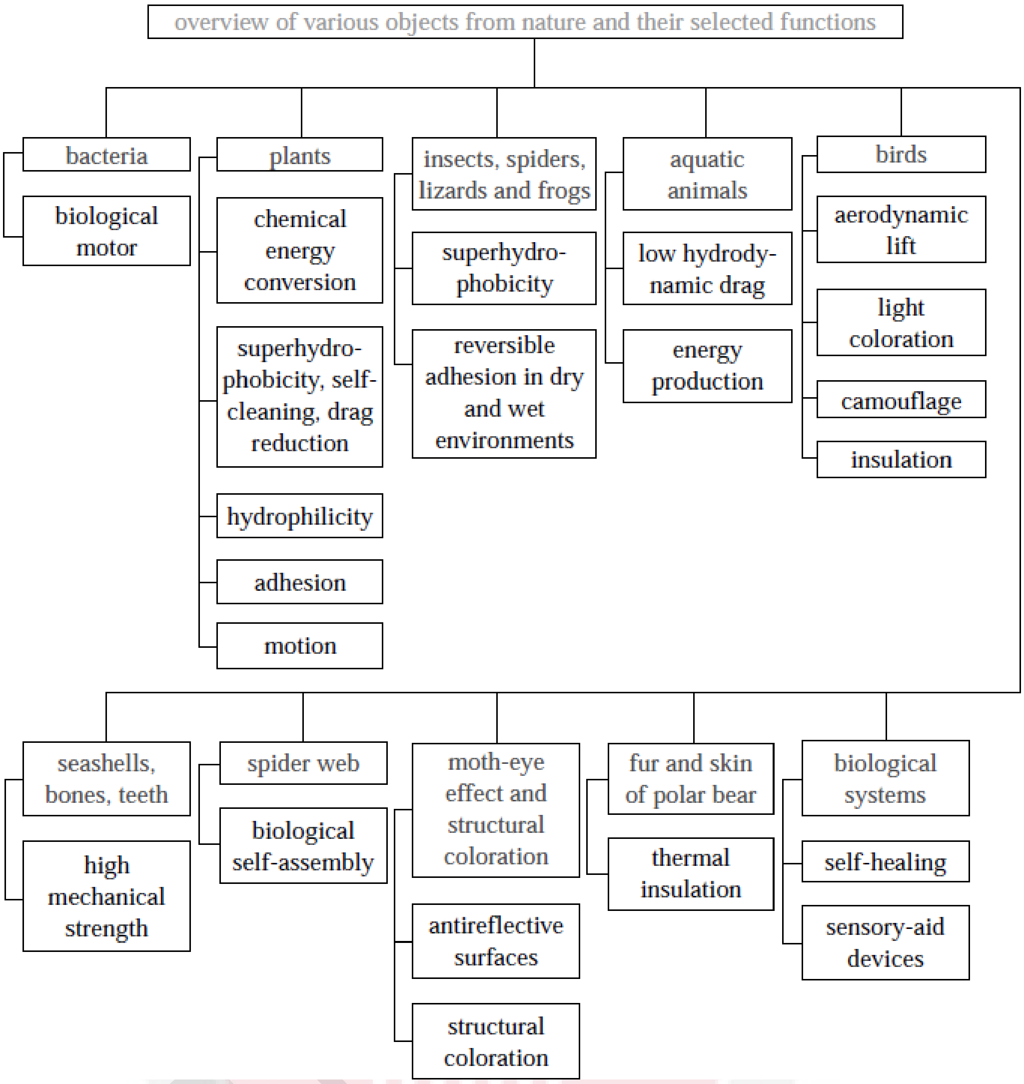

Figure 1.2: The various inspirations and applications of biomimetics Bhushan, (2009)

The successful integration of biomimetics into mechanical systems has been a challenge. Recent technological advancements in the field of material science and engineering have made the dream of mimicking nature a reality (Choi, 2009; Fish, 2008; Fish, 2006). Due to its huge importance, research in the field of biomimetics is gaining popularity.

1.3 Humpback Whale

The humpback whale (*Megaptera Novaeangliea*) is a species of baleen whale of the Balaenopteridae family. This mammal has existed for the past 55 million years and comes under the order of cetaceans, which includes dolphins, whales and porpoises Fish et al., (2011a). This whale has a huge size, measuring approximately 15.6 meters in length and weighing around 34 tons Johnson and Wolman, (1984). Humpback whales feed on plankton, and fish schools of euphausiids, herring, and capelin Fish et al., (2008). The most amazing feature of the humpback is its acrobatic behaviour during feeding known as bubble netting, which involves creating a zone around the prey and then sudden lunging towards it, giving the whale an element of surprise Johnson and Wolman, (1984), Winn and Winn, (1985). Due to the presence of the tubercles on the flippers, the whale has a minimum turning diameter of 14.8m Figure1.3 Summers and Wynne, (2004), Fish, (1999).

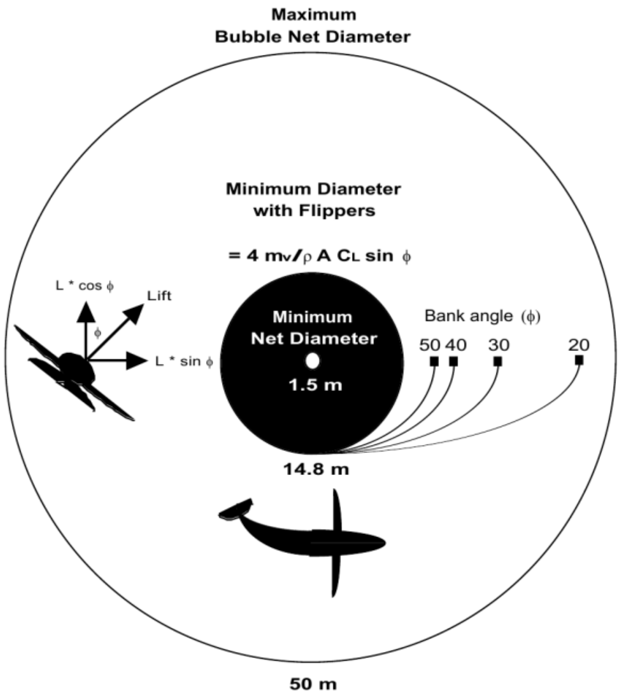

Figure 1.3: Bubble net formation and the turning radius of the humpback Fish, (1999)

Humpbacks can also perform acrobatic manoeuvres and underwater somersaults, (Summers and Wynne, (2004), Johari, et al., (2007). The flippers measure more than 9 meters in length, are elliptical in shape and have a high aspect ratio. The wavy leading edge consists typically of 10 or 11 rounded tubercles Figure 1.4 (Fish and Lauder, 2006; Fish et al., 2008; Fish, 1994; Van Nierop et al., 2008).

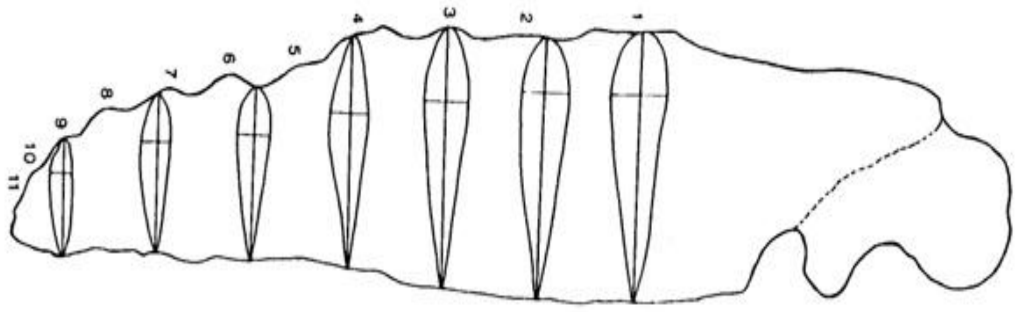

Figure 1.4: Humpback whale flipper with Tubercle locations profile Fish and Battle, (1995)

Figure 1.5: Blade developed by Whale Power Corp Wind Energy Institute of Canada, (2008)

Dr. Frank Fish (a marine biologist) who noticed bumps on the flipper, started the initial research, subsequently publishing numerous research articles on the topic (Fish et al., 2008; Fish and Lauder, 2006, Fish and Lauder,2013; Fish et al., 2011a; Fish et al., 2011b; Fish, 1999; Fish, 2006; Fish, 1994; Fish and Battle, 1995; Watts and Fish, 2001; Watts and Fish, 2002). Watts and Fish patented this technology and started a company named 'Whale Power', which develops wind turbine blades. Figure 1.5 shows the blades incorporated with the tubercle design. The new design has 25% more airflow than conventional wind turbine blades and it produces 20% more energy Watts and Fish, (2002), Wind Energy Institute of Canada, (2008), Yurchenko, (2011).

Fish and Battle, (1995) studied flipper morphology in detail after obtaining a dead humpback whale. The flipper is elliptical and tapered, with a 19º swept angle w.r.t longitudinal axis. Tubercle location is as shown in Figure 1.4 the whale fin obtained consisted of 11 tubercles. The location of first tubercle is at 33% span and 11th tubercle at 99.1% Figure1.4. The flipper profile has a cross-section that is constant, irrespective of the span-wise position, while the chord reduces moving outward. The profile is similar to NACA 63_4-021 airfoil. An analogy between leading edge strakes and tubercles working was drawn Fish and Battle, (1995).

1.4 Low Reynolds Number

Low Reynolds number flows pose a great challenge in the selection of a Turbulence model for simulation. Many of the UAV's and MAV's work in these Reynolds number ranges. Colossal interest is growing in the CFD study of static wing and flapping wing aerodynamics on flow in this regime Gad-el-Hak, (2007).

In the case of low Re airfoils, the resistance to separation of the boundary layer is very poor, thus resulting in a dominant adverse pressure gradient. As flow separates from the point of minimum pressure, due to the increase in adverse pressure at the leading edge, separation takes place. The separated flow is highly unstable, resulting in transition immediately downstream, causing the flow to become turbulent. Thereby turbulent shear stresses energize the flow to counteract the increased adverse pressure, helping the flow to reattach. Thus, a zone in between separation and reattachment is formed, known as the separation bubble (Mueller and Batil, 1982 and Carmichael, 1981). The separation bubble is dependent on the flow Re, the pressure distribution, the curvature of the airfoil, roughness and various other factors Gad-el-Hak, (2007). Two types of separation bubble exist, namely the short bubble and the long bubble Figure 1.6. A short bubble exists when the flow Re is below 10^5 and only extends to a couple of percent along the chord. The stability of this bubble is only for a short duration. Carmichael, (1981) has stated that below Re $5x10^4$, a short laminar separation bubble causes a drastic drop in lift. If the Reynolds number exceeds 10^5, a long bubble is formed. This bubble extends to 20-30% along the chord and affects the flow drastically Lissaman, (1983).

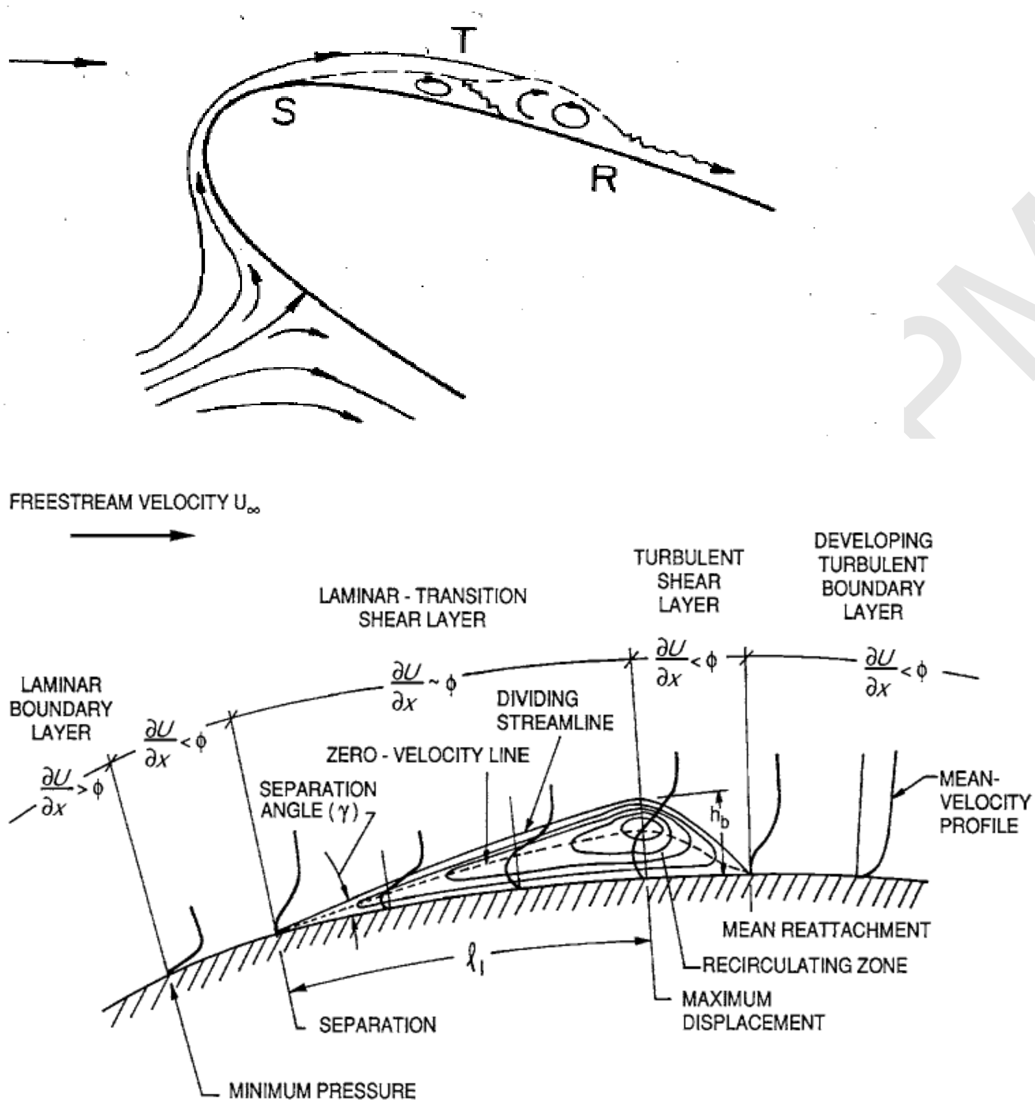

Figure 1.6: Flow separation bubble (Mueller and Batil, 1982; Carmichael, 1981)

For airfoils operating in the Re range of 10^6, the adverse pressure gradient is eliminated by turbulent flow at transition thus preventing separation. An increase in Re induces turbulence in the boundary layer, imparting high energy to oppose separation.

1.5 Vortex Generators

Vortex generator (VG) is most commonly used flow control devices for, low Re flows and to control the formation of separation bubble. A detailed review on types of VG, working mechanism and application is reported by Lin, (2002)

Previous work by Zhen et al., (2011) showed that implementation of VG increased the airfoil performance. Serakawi and Ahmad, (2012) did PIV experimental work and concluded that VG effectively reduce the separation in diffuser. Ahmad et al., (2008) showed the effect of oscillating Sub Boundary Layer Vortex Generator (SBVG) in reducing the separation, Halim and Ahmad, (2013) did simulation to find optimized configuration in order to reduce separation. Aftab and Murthy, (2012) showed that standard VG reduced separation on Onera M6 wing.

1.6 Problem Statement and Hypothesis

Wind turbine blades, trainer aircraft and UAV's operate at low Reynolds number. Thick airfoils are mainly used in these applications, due to its benefit at low speed in generating high lift. Airfoils operating at low speed fall under low Reynolds number range, 100,000 to 500,000 and are prone to the formation of laminar separation bubble. The separation bubble increases drag and reduces the performance of the airfoil. In order to prevent the formation of separation bubble passive and active flow control devices are used. Previous research has shown that installing passive flow control devices such as, VG on the airfoil drastically improves the performance. Recent discovery of tubercle technology has effectively, helped in performance improvement by hindering the formation of separation bubble. Turbulence models used in CFD studies of low Reynolds number flow experience uncertainties, which need to be properly captured. New turbulence models have been developed and are available to address this issue. In the current research the CFD simulations are carried out, on a NACA 4415 airfoil at low Reynolds number of 120,000. The newly developed RANS transition turbulence models are utilised. To check the accuracy and capability of the transition turbulence model to obtain a CFD solution is very essential, to understand the flow characteristics of NACA 4415 airfoil at low Reynolds number. The issue in regard with the effect of tubercles at the leading edge of NACA 4415 needs to be investigated. The author of the current research hypothesizes that favourable performance benefits will results, from the combination two passive flow control devices, tubercles and vortex generators on NACA 4415 airfoil in low Reynolds number range. The author intends to address the gap in knowledge, as well as bring forward a new dimension to low Reynolds number flow control research.

1.7 Aims and Objectives

Tubercles are currently being used to address the problem of separation bubble. Previously, VG's have been used to provide enhancement in airfoil performance. The main aim of the current work is to combine vortex generators with tubercle design, and study the effect on performance of the airfoil for low Reynolds number flows.

To achieve the above aim three objectives have to be achieved as described below

- To investigate and validate an optimal CFD turbulence modeling technique, suitable for low Reynolds number flows.
- To conduct a parametric study to determine the optimal shape for the tubercle and to determine the optimal amplitude and wavelength suitable for the tubercle.

- Implement Vortex Generators (VG) and the optimized tubercle design on the airfoil and determine the effect on performance.

1.8 Scope of work

This research work was carried out in collaboration with CTRM Sdn Bhd, Malaysia. The Aludra MK-I UAV is designed and built by CTRM and is operated by Royal Malaysian Air Force. The airfoil design in the current study is similar to the one on Aludra Mk-I UAV. Based on the TLE airfoil performance benefits, a new wing model will be designed and tested on the Aludra Mk-I UAV. The CFD parametric study on TLE shape and analysis will give a deeper insight into flow behaviour. No extensive research has been reported considering the TLE shape. The fabricated TLE airfoil on which the experimental work is reported in this thesis is first of a kind study. The combination of TLE and VG will result in a deeper understanding of combining two flow control devices.

1.9 Thesis Organization

Chapter 1 introduces to the background of biomimetics, flow control, low Reynolds number, and Vortex Generators (VG). It also highlights the motivation for the study, outlining the scope and objectives of the research.

Chapter 2 summarises the literature available on humpback whale flipper. A detailed in-depth review has been carried out and discussed in this chapter. The chapter deals with studies incorporation tubercle design on various airfoils. The contents of the chapter have been published as a review article in Journal Progress in Aerospace Sciences.

Chapter 3 deals with the numerical and experimental methodology used for conducting the validation study. It also includes the numerical methodology followed in order to carry out the parametric study of Sinusoidal and Spherical shaped tubercles, varying the amplitude and wavelength of the tubercles designs. The fabrication and Wind tunnel calibration methodology employed in open loop wind tunnel test facility at Universiti Putra Malaysia (UPM) has been described in detail in this chapter.

Chapter 4 reports the numerical, results. The validation and verification of the numerical results is reported. The results of the parametric study are also discussed.

Chapter 5 describes the experimental results, performance comparison of airfoil with spherical tubercle and airfoil with VG is reported.

Chapter 6 discusses the benefits of combining two flow control techniques. The results of this unique combination are discussed in detail.

Chapter 7 summarises the overall work along with conclusions and recommendations for future research.

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