NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF 2D MEMBRANE AIRFOIL PERFORMANCE

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NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF 2D MEMBRANE AIRFOIL PERFORMANCE

by

MOHD SHARIZAL BIN ABDUL AZIZ

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"In the name of ALLAH, The Most Beneficent, The Most Merciful"

Praise is exclusively to Allah, the Lord of the universe and peace is upon the Master of the Messengers, his family and companions.

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NOMENCLATURE

Roman symbols

Re	Reynolds number
G_v	production of turbulent viscosity
(x_s/c)	laminar separation point
(x_t/c)	reattachment point
$(x_t - x_s)/c$	length of LSB
c	chord length
C_D	coefficient of drag
C_L	coefficient of lift
C_{Lmax}	maximum lift coefficient
U	free stream velocity

Greek symbols

ν	kinematic viscosity
μ	dynamic viscosity
α	Angle of attack
ρ	fluid density
υ	air kinematic viscosity

Abbreviations

AOA	Angle of attack
AR	Aspect Ratio
CFD	Computational Fluid Dynamics
CSD	Computational Structural Dynamics
DARPA	Defense Advanced Research Projects Agency
FEM	Finite Element Method
FSI	Fluid Structure Interaction
FVM	Fluid Volume Method
L/D	Lift-to Drag ratio
LAR	Low Aspect Ratio
LSB	Laminar Separation Bubble
MAV	Micro Air Vehicle
MpCCI	Mesh based parallel Code Coupling Interface
NACA	(U.S) National Advisory Committee for Aeronautics
PIV	Particle Image Velocimetry
RANS	Reynolds-averaged Navier-Stokes
UAV	Unmanned Air Vehicle
VOF	Volume of fluid

KAJIAN BERANGKA DAN EKSPERIMEN
KE ATAS PRESTASI SAYAP MEMBRAN 2D

ABSTRAK

Kriteria penerbangan haiwan mamalia sering dikaitkan dengan sayap nipis yang bersifat patuh sebagai permukaan untuk daya angkat. Penggunaan sayap yang unik ini terdapat pada mamalia yang boleh terbang seperti kelawar dan tupai terbang. Oleh itu kriteria yang unik ini telah dipelajari untuk meneroka kebolehan sayap membran yang bersifat fleksibel terhadap prestasi aerodinamik. Interaksi bendalir-struktur pada sayap membran sangat kompleks dan jarang diberikan perhatian berbanding sayap tegar. Oleh yang demikian, suatu sayap membran yang dibaluti oleh kepingan lateks pada bingkai sayap model NACA 64_3-218 telah dibangunkan untuk mempelajari kesan kefleksibelan membran terhadap gelembung pembahagian laminar (LSB), kesan ketebalan membran, nombor Reynolds, dan ketegaran membran terhadap prestasi aerodinamik (daya angkat dan daya seret) pada aplikasi nombor Reynolds *(Re)* yang rendah. Simulasi dua dimensi (2D) juga telah dilakukan pada sayap tegar dan sayap membran manakala pemodelan aliran udara dilakukan dengan model Laminar dan model turbulen Spalart-Allmaras dengan mengambil kira keadaan yang berubah dengan masa. Penyelesai aliran bendalir ialah FLUENT 6.3 dan penyelesai struktur ialan ABAQUS 6.8-1, kedua-duanya digabungkan dalam mod masa yang sebenar menggunakan perisian MpCCI 3.1. Ia telah membuktikan bahawa LSB dipengaruhi oleh kefleksibelan membran dan sayap membran mempunyai kriteria pengagihan aliran yang lebih unggul berbanding sayap tegar. Seterusnya, kesan ketebalan kulit dan *Re* terhadap prestasi aerodinamik disiasat. Umumnya, ia telah membuktikan bahawa apabila ketebalan membran dikurangkan,

daya angkat bertambah dan daya seret berkurangan. Oleh yang demikian, ia meningkatkan prestasi aerodinamik; kesamaan pemerhatian juga dilaporkan dengan kes kenaikan *Re.* Tambahan lagi, pembelajaran tentang kesan bilangan rasuk tegar ke atas prestasi aerodinamik juga dikaji dengan kaedah eksperimen. Keputusan menunjukkan bahawa ketegaran kulit membran memberikan kesan kepada prestasi sayap membran; apabila bilangan rasuk tegar dikurangkan, angkatan bertambah manakala seretan berkurangan. Akhir sekali, anjakan dan tekanan pada sayap membran dengan aliran mendatang juga dipelajari dengan teknik simulasi. Hasilnya, ia menunjukkan bahawa sayap membran berubah bentuk dengan aliran mendatang dan tegasan Von Mises menunjukkan taburan yang tidak sekata di sekitar sayap membran. Teknik simulasi disahkan dengan eksperimen terowong angin yang bersesuaian dan padanan yang baik diperolehi.

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF 2D MEMBRANE AIRFOIL PERFORMANCE

ABSTRACT

The characteristic feature of a mammalian flight is the use of thin compliant wings as the lifting surface. This unique feature of flexible membrane wings found in flying mammals such as bats and flying squirrel was studied in order to explore its possibility as flexible membrane wings in aerodynamics performance study. The unsteady aspects of the fluid-structure interaction of membrane wings are very complicated and therefore did not receive much attention compared to the rigid wing. Motivated by this, a membrane airfoil consisting of latex sheet mounted on a NACA 64_3-218 airfoil frame was developed to study effect of membrane flexibility on laminar separation bubble (LSB), effects of membrane thickness, Reynolds number *(Re),* and membrane rigidity on the aerodynamic performance (lift and drag), meant for low *Re* applications. Unsteady, two dimensional (2D) simulations were also carried out on rigid and membrane airfoils with the air flow modeled as Laminar and the turbulent cases being modeled using Spalart-Allmaras viscous model. FLUENT 6.3 was employed to study the fluid flow behavior, whereas ABAQUS 6.8-1 was utilized as structural solver, both of which were coupled in real time using the MpCCI 3.1 software. It has been established that, the LSB is greatly influenced by the membrane flexibility, and the membrane airfoil has superior flow separation characteristics over rigid one. Besides that, the effects of skin thickness and *Re* on the aerodynamic performance are investigated. In general, it was observed that, as the membrane thickness decreases, the lift increases and drag decreases, thereby improving the aerodynamic performance; with similar observation reported for the case with increase in *Re*. Moreover, using experiment, the studies on the effect of ribs on aerodynamic performances were also presented. The results showed that the rigidity of the membrane skins could significantly affect the performance of the membrane airfoils; as the number of rigid ribs decreases, the lift increases and drag decreases. Finally, the displacement and stress of membrane airfoil with incoming flow has been studied by simulation technique. It was found that the membrane airfoils have deformed by the incoming flow and the Von Mises stress was found fluctuating around the membrane airfoil. The current simulation techniques were also validated by suitable wind tunnel experiments and close agreement was obtained.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the recent few years, a lot of research has gone into the development of unmanned aerial vehicles and micro aerial vehicles. Their usage in information gathering has become popular in many countries around the world. This has necessitated a careful research into the design and aerodynamics of these vehicles particularly the more complicated micro aerial vehicles.

Aerodynamics is an applied science with many practical applications in engineering. The term ‘’aerodynamics’’ is generally used for problems arising from flight and other topics involving the flow of air (Anderson, 2001). Aerodynamics is that branch of dynamics which addresses the study of motion of air, particularly when it interacts with a moving object. It is a subfield of fluid dynamics and gas dynamics, with much theory shared between them. There are many ways to identify the problems associated with aerodynamics. The flow environment defines the fundamental criterion. The most common example of aerodynamics is the lift and drag study of an airplane or the shock waves near the nose of a rocket.

1.2 Wing flexibility and design for mammalian flight

The wings of flying mammalian change shape dramatically during flight. This type of flight behavior is very complex, in which air flowing around their wings is being continuously manipulated and the enormous amount of sensory information on the inherently and unstable form of locomotion is processed. Generally, animals perform these complex aerial maneuvers in pursuit of food or to escape from enemies, or to avoid collisions. These behaviors involve the integration of neural control, musculoskeletal dynamics, aerodynamic and inertial force, and three- dimensional shape of flexible wing. Thus a thorough understanding of animal flight requires knowledge of the biological process, physical forces involved, and the interactions between these constituent parts (Combes, 2002).

Galvao et al., (2006) proposed the use of thin compliant wings as the lifting surface. Wings composed of thin, compliant skin membranes are used by several vertebrate species, most notably by flying and gliding mammals such as bats, flying squirrels, and marsupial gliders. These animals exhibit extraordinary flight capabilities with respect to maneuvering and agility that are not observed in other species of comparable size. Song et al., (2008) has studied birds extensively, and has observed that they have relatively rigid wings with limited degrees of freedom, whereas insect flight, which occurs at much lower Reynolds numbers, can be characterized by the relatively simple articulated flapping motion of effectively rigid wing. On the other hand Hu et al., (2008) who studied bats, has observed an extremely high degree of articulation in the wing (the elbow, wrist, and finger joints). The wing surface of bats is composed of a thin flexible membrane (Hu et al., 2008). These morphological features may be key in enabling bats to fly in such a remarkable fashion, however information regarding their aerodynamic performance of flying vehicles with either highly articulated or compliant wings are not well known (Song et al., 2008). The skin of the bat wing is known to exhibit substantial changes in shape and camber throughout the wing beat cycle while the effects of multiple joints and anisotropic membrane stiffness across the wing (Rojratsirikul et al., 2009) are not understood. Even though the study of the full complexity of mammalian flight is challenging, recent studies have shown considerable progress. Most studies have focused on the overall lift and drag characteristics (Swartz et al., 2005, Tian et al., 2006, Bishop, 2006), their animal's kinematic motion (Tian et al., 2006, Riskin et al., 2008), or the wake characteristics behind the animal (Tian et al., 2006, Hedenstrom et al., 2007). Furthermore, it is not impossible to isolate the individual contribution of the various, interdependent aspects of an animal's morphology to its overall aerodynamic performance. According to Song et al., (2008) one solution to these difficulties is to test, using more traditional engineering models, the key features of the biological system with the goal of understanding how each feature influences the aerodynamic performance of the complete animal.

Recent studies indicate that the interest in micro sized aircraft projects have increased gradually. In general, these studies are focused on low Reynolds number, low aspect ratio (LAR) aerodynamics study. Some major studies in this field have been carried out by Galvao et al., (2006), Shyy et al., (2005b), Shyy, (1999), Torres and Mueller, (2004). Norberg, (1990) and Bishop, (2006) have observed that the flying and gliding mammals, such as bats, flying squirrels and marsupial gliders have this unique LAR wings composed of thin and very flexible membranes which exhibit extraordinary flight capabilities with respect to maneuvering and agility and are not found in other species of comparable size. It can thus be inferred from the observations and findings of previous studies that the incorporation of flexible membranes as lifting surfaces is advantageous in the use with maneuverable Micro Air Vehicles (MAVs).

1.3 Motivation for Research: Small UAVs and MAVs

A great deal of interest has emerged during the last half-decade for a totally new kind of unmanned air vehicle. Although large unmanned aircraft such as Pioneer, Hunter, and Predator have been successful for many years for military reconnaissance applications, there is visible demand for much smaller, platoon-level unmanned aircrafts (Torres, 2002). Recent developments like the small UAVs such as the Pointer, Sender, and the Dragon Eye, have performed satisfactorily.

Membrane wings are used in many engineering applications including parachutes, micro light, paraglide and hang glider wings, yacht sails, and wings of small unmanned air vehicles (Shyy, 1999). All these years, flight vehicles have been primarily manned or man controlled, using human sensors, or sensors controlled by humans to complete the mission of the flight. The future expectation in aviation sector is autonomous flight vehicles and vehicles that can complete missions with as little human guidance as possible and rely solely on their electronic and automated sensors to realize given tasks. Strides towards this goal have already been made as there are currently UAVs (Unmanned Air Vehicles) capable of flying missions; primarily as military surveillance. However, these vehicles are made of macro scale – of the same order in size as manned aircraft. The full potential of completely automated air vehicles, which are a miniaturized version, can be utilized to fly through crowded localities or even through buildings or building rubble to carry out their missions. The term Micro Air Vehicle (MAV) has been used to describe these small scale vehicles (Murphy, 2008). These MAVs can be employed in the areas of environmental monitoring and also military applications. Their small size and flight regime, the coupled with aerodynamics, flight dynamics, and structural dynamics makes their understanding complicated (Chimakurthi et al., 2009).

MAVs are very useful and can be employed in many lifesaving applications. The small scale of MAVs makes it necessary to it to be very lightweight and made of compact components. For such application, membrane wings are generally preferred because it can facilitate passive shape adaptation (Lian and Shyy, 2007) resulting in delayed stall and their inherently light-weight nature as well as variable camber feature (Rojratsirikul et al., 2009). MAVs with a maximal dimension of 15 cm or less and a flight speed of 10–20 m/ s are of interest to both military and civilian applications. Shyy et al., (2005a) has classified several prominent features of MAV flight. They are (i) low Reynolds number (10^4–10^5), resulting in degraded aerodynamic performance, (ii) small physical dimensions, resulting in certain favorable scaling characteristics including structural strength, reduced stall speed, and impact tolerance, and (iii) low flight speed, resulting in order one effect of the flight environment and intrinsically unsteady flight characteristics. He has further proposed that these vehicles could be effectively employed to perform reconnaissance, targeting, surveillance, and bio-chemical sensing at a remote or otherwise hazardous location. Stanford, (2008) has observed that MAVs could also play a significant role in environmental agriculture, wildlife, and traffic-monitoring applications other their conventional military and defense related applications like over-the-hill battlefield surveillance bomb damage assessment chemical weapon detection etc. Shyy et al., (2005a) in their research study compared rigid wing with a membrane wing and determined that the later can better adapt to the stall and has the potential for morphing to achieve enhanced agility and storage consideration. The recent advances in the field of material science, fabrication technology, electronics, propulsion, actuators, sensors, modeling, and control has made micro air vehicles (MAVs) useful for many applications. Examples of successfully designed, built, and flight tested MAV platforms can be seen in the work of Ailinger, (1999), Torres and Mueller, (2000), Grasmeyer and Keenon, (2001), Ifju et al., (2003), Shkarayez et al., (2004), and Sun et al., (2005) among many others (Stanford, 2008). Current designs for airfoils/wings for MAVs have been developed in the shadows of macro scale airfoils/wings and are a scaled down versions of the same. Although proven for their own applications, these airfoils may not be suitable in the low Reynolds number regimes associated with MAVs.

Classical aerodynamics theory provides reasonable accurate performance predictions for airplanes flying at Reynolds number larger than approximately one million (Smith and Shyy, 1996). However, the low Reynolds number condition presents numerous challenges on MAVs because they are susceptibility to flow separation and low lift-to-drag ratio. The much lower operating Reynolds numbers of MAVs introduces new difficulties in terms of predicting aerodynamics forces. Lian et al., (2003) has demonstrated that in the range of Reynolds number of 10^4–10^6; complex flow phenomena often take place on the upper wing surface, such as laminar boundary layer separation, transition, and reattachment. Thus the low aspect ratio wing exhibits clear vertical structures. Consequently, it has a higher angle of attack because tip vortices provide additional lift force by creating low-pressure zones, which is similar to delta wings. However, the low aspect ratio was found to increase the induced drag. They also determined that the vortical flow causes rolling instability of the small vehicle, especially when the vortex strength is not equal on the two sides (Lian et al., 2003). Similar numerical investigations are reported by Lian and Shyy, (2003) and Viieru et al., (2003), and the experimental with respect to MAV's were carried out by Palletier and Mueller, (2000).

There is considerable difficulty in developing aircraft with inherently low aspect ratios which can operate at low Reynolds numbers (Torres, 2002). A need therefore exists for detailed aerodynamic analysis tools that are applicable to the Reynolds number and aspect ratio operating conditions found in MAVs and in some small UAVs.

1.4 Exploring Biologically-Inspired Membrane Airfoils

1.4.1 Introduction to Flexible Membrane Airfoils

Tamai, (2007) has provided a detailed investigation into the use of flexible membrane airfoils. Unlike their commercial airfoils, flying species such as flying mammals have non-rigid wings. These flying mammals' wings are composed of membrane structure having flexible skin. These have evolved over a period of over 150 million years and demonstrate much better aerodynamic performances when compared to the commercial airfoils which have only been developed in the last one hundred years. Tamai, (2007) has also observed that the flexible airfoils deform continuously under low-Reynolds number flight, which assists the airfoil structure to absorb the uncertainties in the air currents thereby improving its stability

1.5 Problem Statement

Flow over a compliant membrane is a complex problem where the interaction between fluid and membrane determines the nature of the aerodynamic characteristics of the membrane wing. Even though many numerical studies on the behavior of membrane wings have been developed, the previous researchers performed fluid flow and structural analyses independently of each other, with manual interfacing. In the present study, the recently introduced Mesh based parallel Code Coupling Interface (MpCCI) technique is employed to facilitate the coupled real-time analysis of both fluid flow, and structural deformation of the airfoil membrane. By the use of MpCCI, the analysis of FSI problem is expected to be simpler, realistic, effective and accurate, compared to the manual coupling. The work presented in this proposal is expected to provide initial design guidelines for the practical design and implementation of membrane skin into aviation field.

1.6 Research Objectives

The objectives of this research are:

1. To study the flow behavior on 2D membrane and rigid airfoils using numerical and experimental methods.
2. To carry out parametric study at different Reynolds number, membrane thickness, effect of ribs on the aerodynamic performance characteristics of a membrane airfoil.
3. To carry out fluid structure interaction and study the effect of membrane deformation and stress distribution on the airfoil.

1.7 Scope of the research work

In this research work, the simulation of fluid flow is focused on two dimensional (2D) NACA 64_3-$_2$18 rigid and four types of membrane airfoils are used to investigate the unsteady aspects of the fluid-structure interaction on aerodynamic performance. This research also concentrates on low Reynolds number applications (Re= 2738-10269) with the air flow modeled as Laminar and turbulent cases being modeled using Spalart-Allmaras viscous model. The validation of the FSI software on solving fluid flow behavior is performed with the flow visualization and lift-drag experiments using low-speed air chamber nozzle and open circuit wind tunnel. The effect of membrane deformation and stress distribution on the membrane airfoil is also included in the investigation and the qualitative technique is used to validate the simulation results.

1.8 Thesis outline

This thesis is organized into five chapters. Brief presentation about wing flexibility, UAVs and MAVs, biologically-inspired airfoils, problem statement, research objectives, and scope of the research work have been introduced in chapter one. Literature review of this study is presented in chapter 2. In chapter 3, the methodology in numerical and experimental method is highlighted. The comparison of experimental results and simulated results are discussed in chapter 4. Finally, concluding remarks and recommendation for future works are presented in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is intended to review the previous works that relate to the current study. For the first sub-chapter, a brief introduction about Micro Air Vehicle is presented. The second and third sub-chapter reviewed the laminar separation bubble and aerodynamic performance studies. The fourth sub-chapter presents the approach of numerical setting and configurations that have been applied. The summary of the literature review is presented at the end of this chapter to support the simulation and experimental work that has been done in this study.

2.2 Micro Air Vehicle (MAV)

The Defense Advanced Research Projects Agency (DARPA) defined MAV as an aerial vehicle having maximum dimension of 15 cm and total weight of 100 grams. Thus, the size and weight constraint derived from both physical and technological considerations have made MAVs at least an order of magnitude smaller than other Unmanned Air Vehicles or UAVs (S. Beerinder, 2006). Many studies on the membrane behavior and aerodynamics, inspired by MAV applications have been reported in this area.

Shyy et al., (1999) studied the scaling laws of biological and MAVs involving wing span, wing loading, vehicle mass, cruising speed, flapping frequency, and power. The kinematics of flapping wings and aerodynamic models for analyzing lift, drag and power, and the issues related to low Reynolds number flows and airfoil shape selection were also discussed. It was observed that flapping wing dynamics and many aspects of low Reynolds number flight involve large-scale vortical motion and detached flows, and require the full Navier Stokes flow model to be employed theoretically to understand many of the relevant issues.

An experimental investigation on measuring the lift, drag, and pitching moment about the quarter chord on a series of thin flat plates and cambered plates at chord Reynolds numbers varying between 60,000 and 200,000 of MAV has been reported by Palletier and Mueller, (2000). They found that the cambered plates offer better aerodynamic characteristics and the trailing-edge geometry of the wings and the turbulence intensity in the wind tunnel do not have a strong effect on the lift and drag for thin wings at low Reynolds numbers. Lian et al., (2003) reported the aerodynamics of membrane and rigid wings under the MAV flight conditions. Structural dynamics in response to the surrounding flow field is presented to highlight the multiple time-scale phenomena. It was observed that tip vortices reduce the effective angle while bringing low-pressure regions which provide additional lift force for the low aspect ratio wing.

Viieru et al., (2005) used the endplate concept to help probe the tip-vortex effects and solving the Navier–Stokes equations around a rigid wing with a root-chord Reynolds number of $9\times10^{4.}$ They observed that with modest angles of attack the endplate can improve the lift-to-drag ratio by reducing the drag, while, the wing tip vortex is stronger and the endplate loses its effectiveness; as the angle of attack becomes substantial. Shyy et al., (2005b) also studied the flow structures associated with the low Reynolds number and low aspect ratio wing, such as pressure distribution, separation bubble, and tip vortex, as well as structural dynamics in response to the surrounding flow field under the MAV flight condition, by developing an automated wing shape optimization technique. The understanding of the key issues related to robust and stable flight and vehicle durability was improved.

Null and Shkarayev, (2005) performed an experimental analysis to study the effect of camber on the aerodynamics of adaptive MAVs. They tested four models with 3, 6, 9, and 12% camber in the low speed wind tunnel at angles of attack ranging from 0^o to 35^o and velocities of 5, 7.5, and 10 m/s, corresponding to Reynolds numbers of 5×10^4, 7.5×10^4, and 1×10^5 respectively. The 3% camber wing gave the best lift-to-drag ratio cambers and would be the optimal choice for high-speed, efficient flight while the 6 and 9% camber wings showed the best low-speed performance because of their high lift-to-drag ratios and mild pitching moments near their stall angles of attack. An energetic-based design of a mechanical flapping-wing machine had been carried out by Madangopal et al., (2006). The design makes use of tension and they increase the torque during the upstroke and reduce the same during the down stroke, thereby reducing the sharp variation in the torque over the entire cycle and keeping its value within the peak torque requirements of the drive motor.

Lin et al., (2007) developed a Gottingen camber airfoil, a swept-back leading edge and a straight trailing edge to explore the aerodynamic performance of wings with different shapes at low Reynolds numbers. Test was carried out in the low-speed open-circuit wind tunnel. They found that the wings with Gottingen camber have a superior lift and lift-to-drag ratio, while the wings with dragonfly like airfoils perform well in terms of drag and pitch moment. Yang et al., (2007) proposed using "flexible" carbon-fibers and parylene (poly-para-xylylene) films as the wing frames for palm-size MAVs with the wingspan of 21.6 cm. The time-averaged lift, thrust coefficients and the structure aging of MAVs have been investigated to identify the influence of this figure-of eight flapping. The biomimetic figure-of eight is done by the very nature of the aero-elastic interaction as well as the symmetry breaking of a simple flapping system.

The elastic deformations and corresponding aerodynamic coefficients of flexible wings used for MAVs were developed by Albertani et al., (2007). The low aspect ratio wings incorporate an elastic latex membrane skin covering a thin carbon fiber skeleton and were tested in a unique low-speed wind tunnel facility integrating a visual image correlation (VIC) system with a six-component strain gauge sting balance. The passive wing flexibility preferably affects aerodynamic performance when compared to a rigid model of similar geometry. A water tunnel study of the effect of spanwise flexibility on the thrust, lift and propulsive efficiency of a rectangular wing oscillating in pure heave has been performed by Heathcote et al., (2008). The thrust and lift forces were measured with a force balance, and the flow field was measured with a Particle Image Velocimetry (PIV) system. The range of Strouhal numbers for which spanwise flexibility was found to offer benefits overlaps the range found in nature, of $0.2<Sr<0.4$. The flexibility may benefit flapping-wing MAVs both aerodynamically and in the inherent lightness of flexible structures.

Another effect of wing flexibility on the aerodynamics of a flapping wing MAV has been investigated experimentally by Lunsford and Jacob, (2008). Seven different wing configurations comprising of combinations of three different wing flexibilities were tested in quiescent flow and at wind tunnel velocities of 3.0 and 5.4 meters per second. The static tests were run at flapping frequencies of 4.8, 5.8, and 6.8 Hz. The flexibility and configuration of the wings have a noticeable effect on performance of a flapping wing MAV. Watman and Furukawa, (2008) conducted a visualization system for analysis of MAV scaled flapping wings. The effectiveness of the system was demonstrated in a flow visualization experiment to capture images of the average airflow around a flapping wing at several wing phases. The experiment result indicated the potential of the developed system to considerably improve visualization analysis of MAV scaled flapping wings.

An experimental study to explore the benefits of using flexible membrane airfoils/wings for MAV applications was performed by Tamai et al., (2008). A high-resolution PIV system was used to carry out flow field measurements to quantify the transient behavior of vortex and turbulent flow structures around the flexible membrane airfoils/wings at different angles of attack. The flexibility of the membrane skins changed their camber to adapt incoming flows to balance the pressure differences applied on the upper and lower surfaces of the airfoils. The deformation reduced the effective angle of attack of the airfoils to delay airfoil stall. A study concerning the lift and drag of MAV numerical simulations and experimental measurements was conducted by Khambatta et al., (2008) by comparing with measurements from a sting balance. An experimental PIV measurement were performed under identical conditions (*Re* number and angle of attack) and compared with the numerical solutions. They found an additional discrepancy in the prediction of the magnitudes of the wing-tip vortex; the numerical prediction being smaller compared with the experiment.

Furthermore Mastramico and Hubner, (2008) reported wake measurements behind thin plates with extensible membranes in low-Re flow (Re = 45,000) for flat and cambered with membrane surfaces and rounded leading-edges. In this study hot-film anemometry testing was carried out in the low-speed wind tunnel for batten reinforced membrane cells (free trailing-edge) and perimeter reinforced membrane cells (fixed trailing-edge). They found that the 20% scalloped version of the flat and cambered batten-reinforced plates provided most dramatic effect on the wake structure, resulting in lower profile drag and well-defined spectral peaks. In addition Tang et al., (2008) presented the analysis of fluid-structure coupling procedure between a Navier- Stokes solver and a three-dimensional FEM beam solver for NACA0012 wing of aspect ratio 3. The fluid model includes laminar, the $k-\varepsilon$ turbulence closure, and a filter-based $k-\varepsilon$ closure were used and the structural model was based on an asymptotic approximation to the equations of elasticity. The results were compared against available experimental data. The results confirmed that as fluid density increases, the phase lag of the wing tip displacement relative to the flapping motion becomes more pronounced.

Stanford et al., (2008) had focused experimental and numerical analysis of low aspect ratio and low Reynolds number for fixed membrane wings. Flexible wing structures with geometric and aerodynamic twist were considered. These results indicated that unconventional aeroelastic tailoring can be used to improve MAV wing performance. Liu et al., (2008) has carried out an optimization design for MAV flapping mechanism using Hooke-Jeeves method under the restraint conditions of mechanics, bionics and aerodynamics. The biomimetic wings design and modal were studied using finite element method by considering parameters such as aspect ratio and key node coordinates of wing's nervure. The consideration on those parameters and variables found an efficient and energy-saving driving mechanism, and improved movement balance, energy utilization and flight stability of the flapping-wing MAV.

Numerical simulation with the coupled finite element method (FEM) and the volume of fluid (VOF) technique was applied in the Chimakurthi et al., (2009) work on flapping and flexible wings using NACA0012 model. The structural model used are UM/NLABS and MSC. Marc. The flow solver employed a well-tested pressure-based algorithm implemented in STREAM. It was shown that spanwise flexibility has a favorable impact on the thrust generation and the leading-edge suction to be important for thrust generation in plunging wings with leading-edge curvature. In the range of reduced frequencies, increasing the reduced frequency increased the thrust generated by both rigid and flexible wings. In the case of the flexible wing, the tip displacement increased over the entire range of reduced frequencies. Lentink et al., (2009) designed a flapping MAV to fly both fast and slow, hover, and take-off and land vertically. The scaling laws and structural wing designs to miniaturize the designs to insect size was studied. They found that the flapping MAVs are fundamentally much less energy efficient and insect-sized MAVs are most energy effective when propelled by spinning wings.

Tsai and Fu, (2009) designed and analyzed the aerodynamics performance of flapping wing MAV. The 3D aerodynamic calculation and flow field simulation of a planar membrane wing as shape airfoil for a MAV were studied. The concept of four-bar linkage to design a flapping mechanism which simulates the flapping motion of a bird has been employed. It was observed that the rigidity of tail wing improved the flapping-wing of MAV. In addition Mueller et al., (2010) studied the effects of the thrust and lift force generated as a function of the flapping wing MAV on the new test stand. The model predictions and experimental measurements revealed the detrimental influence of excessive compliance on drag forces during high frequency operation.

Tay and Lim, (2010) investigated the effect of active chord wise flexing on the lift, thrust and propulsive efficiency of three types of airfoils, NACA0012, NACA6302 and the Selig S1020. The airfoils are simulated to flap with four configurations and the factors studied are the flexing center location, standard two-sided flexing as well as a type of single-sided flexing. It was observed that flexing is not necessarily beneficial for the performance of the airfoils. Moreover, efficiency is as high as 0.76 by placing the flexing centre at the trailing edge and the average thrust coefficient is more than twice as high, from 1.63 to 3.57 with flapping and flexing under the right conditions.

Recent progress in flapping wing aerodynamics and aeroelasticity has been carried out by Shyy et al., (2009), Shyy et al., (2010). They found that a variation of the Reynolds number (wing sizing, flapping frequency, etc.) leads to a change in the leading edge vortex and spanwise flow structures. The combined effect of the tip vortices, the leading edge vortex, and jet can improve the aerodynamics of a flapping wing. For fixed wings, membrane materials show self-initiated vibration while for flapping wings, structural flexibility can improve leading-edge suction by increasing the effective angle of attack, resulting in higher thrust generation. Ifju et al., (2002) demonstrated an experimental study to characterize the deformations of flexible wings with a carbon fiber skeleton and thin/ extensible membrane skin for MAVs. A combination of digital image correlation system and a low speed wind tunnel was applied. The displacements were recorded for various wind velocities and angles of attack. In this work Ifju et al., (2002) found that the wings experienced a combination of billowing, washout and bending.

2.3 Laminar Separation Bubble (LSB)

Laminar separation bubble (LSB) size depends on Reynolds number (*Re*). The LSB size is important in determining the airfoil performance. As per Gad-El-Hak, (1989) short bubble is able to provide higher lift to drag (L/D) ratio when compared to the long bubble. For fixed airfoil, the short bubble size decreases when angle of attack is increased. Additionally Mueller et al., (2003) observed that the bubble burst on the airfoil surface under stall condition. Thus, bubble drag is expected in the presence of LSB. Airfoil drag is predominantly due to skin friction and pressure drag including boundary layer displacement effects and flow separation (Gad-El-Hak, 1989). Gad-El-Hak, (1989) has also observed that LSB degrades the generation of lift and drag under low *Re*. However, its effect on airfoil lift is small since it only slightly diminishes the upper surface peak pressure of the airfoil (Reid, 2006).

The interaction between a flexible structure and the surrounding fluid gives rise to a variety of phenomena in engineering applications such as, stability analysis of airplane wings, turbo machinery design, design of bridges, and flow of blood through arteries. Studying these phenomena requires coupled modeling of both fluid and structure (Kamakoti and Shyy, 2004). The performance of an aircraft is strongly influenced by LSB which may occur at low *Re*. LSB is caused by a strong adverse pressure gradient which makes the laminar boundary layer to separate from the curved airfoil surface. This separated flow reattaches to the surface further downstream, forming a separation bubble in the region near the leading edge. The presence of LSB significantly reduces the lift and moment properties and increases the drag. The investigation of flow separation over a thin membrane mounted on an airfoil frame is more complex than that over rigid airfoils. The membrane shapes will change and cause either positive or negative displacements by fluid stresses. The deformation brings a different pressure and stress over the membrane when exposed to a fluid flow. In the recent past, many researchers have reported the use of computational fluid structure interaction (FSI) techniques to study the aerodynamics of aircraft wings. A brief review of the pertinent literature is presented here.

Effect of laminar-turbulent transition on the aerodynamic performance of MAV was studied by Lian and Shyy, (2007) who coupled a Navier–Stokes solver, the e^N transition model, and a Reynolds-averaged two-equation closure to study the low *Re* flow characterized with the laminar separation bubble and transition. A new intermittency function was proposed and tested. Rojratsirikul et al., (2009) addressed the unsteady aspects of the fluid–structure interactions of membrane airfoils. Experiments were performed on two dimensional (2D) membrane airfoils at low *Re*. While the mean membrane shape was not very sensitive to angle of attack (AOA, denoted as α henceforth), the amplitude and mode of the vibrations of the membrane depended on the relative location and the magnitude of the unsteadiness of the separated shear layer. Comparison of rigid and flexible membrane airfoils showed that the flexibility might delay the stall. Subsequently Rojratsirikul et al., (2010), they studied the effects of membrane pre-strain and excess length. Membrane airfoils with excess length exhibited higher vibration modes, earlier roll-up of vortices, and smaller separated flow regions, whereas the membranes with pre-strain generally behaved more similarly to a rigid airfoil.

Molki and Breuer, (2010) numerically investigated the deformation and oscillatory motion of a membrane under aerodynamic loading. A mostly asymmetric deflection with the point of maximum camber was noticed nearly at 40% of the chord length from the leading edge. The deflection was decreased with prestrain, and increased with *Re*. Moreover, the lift coefficient generally increased with α. The drag coefficient was much higher than that of conventional airfoils. Similar studies were reported by Gordnier, (2009) and Gordnier and Attar, (2009), who used sixth-order Navier–Stokes solver coupled with a membrane structural model suitable for the highly nonlinear structural response of the membrane. Visbal et al., (2009) focused on LAR transitional flows over moving and flexible canonical configurations motivated by small natural and man-made flyers. They addressed three separate fluid dynamic phenomena including: laminar separation and transition over a stationary airfoil, transition effects on the dynamic stall vortex generated by a plunging airfoil, and the effect of flexibility on the flow structure above a membrane airfoil. Attar and Gordnier, (2009) performed similar analysis on a plunging one-dimensional membrane.

2.4 Aerodynamics Performance

Analysis of the aerodynamics of aircraft wings is a typical fluid-structure interaction problem (FSI), and substantial works have been reported in this area. An unsteady potential flow analysis incorporating wing flexion to obtain optimal wing shape under varying degrees of unsteady motion and wing flexion was reported by Combes and Daniel, (2001). They focused on forward flapping flight and examined the effects of wing/fin morphology and movements on thrust generation and efficiency. It was shown that aspect ratio and the proportion of area in the outer one-fifth of the wing could characterize wing shape in terms of aero- or hydrodynamic performance. Emulating dragonfly's flexible wing during hovering, Hamamoto et al., (2005), Hamamoto et al., (2007) developed two models of middle-size and high-aspect ratio wings for flapping flight, and tested by fluid-structure interaction (FSI) simulation based on arbitrary Lagrangian-Eulerian method (ALE-FEM). They also compared the aerodynamic performances of these flexible wings with those of rigid wing. Galvao et al., (2006) and Song et al., (2008) studied the aerodynamic performance of thin compliant wings. They found that, in comparison with rigid wings, compliant wings have higher lift slope, maximum lift coefficients, and delayed stall to higher angles of attack. The wings were fabricated with stainless steel frame and latex membrane.

Lian and Shyy, (2007) investigated the effect of laminar-turbulent transition on the aerodynamic performance of MAVs, by coupling a Navier–Stokes solver, the e^N transition model, and a Reynolds-averaged two-equation closure. They tested the performance of a rigid airfoil and a flexible airfoil, mounted with a flexible membrane structure on the upper surface, using SD7003 as the configuration. It was observed that the self-excited flexible surface vibration affected the separation and transition positions, while the time-averaged lift and drag coefficients were close to those of the rigid airfoil. Warkentin and DeLaurier, (2007) conducted wind tunnel experiments on an ornithopter configuration consisting of two sets of symmetrically flapping wings, arranged in tandem. It was discovered that the tandem arrangement could give thrust, and efficiency increased over a single set of flapping wings for certain relative phase angles and longitudinal spacing between the wing sets. Kim et al., (2008) performed structural analysis of a smart flapping wing with a macro-fiber composite (MFC) actuator to determine the wing configuration for maximum camber motion. The effect of spanwise flexibility on the thrust, lift and propulsive efficiency of a rectangular wing oscillating in pure heave was studied by Heathcote et al., (2008). The drag and lift forces were measured with a force balance, and the flow field was measured with a PIV system. They found that introducing a degree of spanwise flexibility was beneficial.

Attar and Gordnier, (2009) performed FSI analysis of a plunging one-dimensional membrane, for MAV applications. A sixth-order Navier-Stokes solver coupled to a finite element solution of a two degree of freedom nonlinear string model were coupled and used to perform high fidelity aeroelastic computations. The effect of the plunging Strouhal number and reduced frequencies along with the static angle of attack of plunging was examined. Similar study on a two-dimensional flexible membrane wing airfoil was reported by Gordnier, (2009) who found that the membrane flexibility imparted a mean camber to the membrane airfoil. The mean camber and the dynamic structural response resulted in a delay in stall with enhanced lift for higher angles of attack. Visbal et al., (2009) analyzed low-Reynolds-number transitional flows over moving and flexible canonical configurations motivated by small natural and man-made flyers. Laminar separation and transition over a stationary airfoil, transition effects on the dynamic stall vortex generated by a plunging airfoil, and the effect of flexibility on the flow structure above a membrane airfoil, were addressed. Mazaheri and Ebrahimi, (2010a), Mazaheri and Ebrahimi, (2010b) experimentally investigated the effect of twisting stiffness of flexible wings on hovering and cruising aerodynamic performance. A flapping-wing system and an experimental setup were designed and built to measure the unsteady aerodynamic and inertial forces, power usage, and angular speed of the flapping wing motion for different flapping frequencies and for various wings with different chordwise flexibility. The effect of compliance on the generation of thrust and lift forces was measured by Mueller et al., (2010) using a new test stand design that used a 250 g load cell along with a rigid linear air bearing. The influence of excessive compliance on drag forces during high frequency operation was found to be detrimental. The compliance could generate extra drag at the beginning and end of upstrokes and downstrokes of the flapping motion.

While focusing on insect flight aerodynamics, Liang et al., (2009) demonstrated that the aerodynamic force production generally decreased with increasing flexibility. Both lift and drag coefficients of wings were greater when wings were more rigid. However, at very high angles of attack, flexible wings generated greater lift than a rigid wing. They also proved that the wing veins could substantially increase the functional rigidity of the wings thereby enhancing its aerodynamic performance. Molki and Breuer, (2010) focused on oscillatory motion of a membrane under aerodynamic loading. They observed a mostly asymmetric deflection with the point of maximum camber located nearly at 40% of the chord length from the leading edge. The oscillations were caused by the oscillatory nature of the flow due to fluid–membrane interaction and the formation of the leading edge and trailing edge vortices. Hu et al., (2010) studied the aerodynamic benefits of flexible membrane wings for the development of flapping wing MAV. The time-averaged lift and drag generation of flexible nylon wing and a more flexible latex wing were compared with those of a rigid wing. The rigid wing exhibited better lift; the latex wing showed best drag generation and the nylon wing was found to be the worst.

2.5 Numerical setting and configurations

2.5.1 Motivation for Two-Dimensional Computational Analysis

The availability of a well established knowledge base, commensurate with the ever increasing computational abilities has allowed the three dimensional analysis of complex aerodynamic configurations and phenomenon. These views may be justified when the end goal is the design of a specific device for a particular application, or to expand the level of understanding beyond the limits of two-dimensional study. However, the objective of present work encompasses something entirely different. The existing knowledge-base low Reynolds number pertaining to applied aerodynamics, airfoils, and flight vehicle design is minimal. There is a need for explorations of these areas, taking into account the limited time and resources, thus sufficing the two-dimensional study of the subject concerned. The analyses are relatively fast, and providing large and varied test parametric studies. This is essential when the investigation is broadly exploratory both in geometry and flow properties. Two-dimensional analysis can also provide a more informative picture of fundamental behavior, free from three-dimensional effects such as cross-flow and induced drag which can be difficult to discern and isolate in both computational and experimental results (Kunz, 2003). Two-dimensional simulations were carried out by a number of researchers Jenkyn, (1996), Kunz, (2003), Ho, (2003), Bletzinger et al., (2006b), Relvas and Suleman, (2006), Liani et al., (2007), Lian and Shyy, (2007), Zhu, (2007), Svácek et al., (2007), Wuchner et al., (2007), Wuchner et al., (2008), Gordnier, (2009), Visbal et al., (2009), Tay and Lim, (2010), and Molki and Breuer, (2010).

2.5.2 Structured Mesh

Computational Fluid Dynamics (CFD) is a valuable tool with the ability to investigate fluid flow over fixed and membrane airfoils. In the pre-processing stage CFD simulations with structured grids can give faster solutions when compared to unstructured grids. In many practical aerodynamic problems involving complex geometries, it may be very time consuming to create structured grids, although it is possible. Therefore, unstructured grids are preferable in some complex cases. However for this case involving two dimensional simulation analysis, fully structured grids are chosen. A compromise is necessary when selecting the type of the grids, computational expense, solution accuracy and computational size, based on the setup time. In order to ensure the accuracy of the flow simulation near the wall surfaces, the y+ values of cell centers adjacent to the wall surfaces need to be in a specific range (Ahmad, 2006); the best value of y+ for the standard Spalart-Allmaras model with standard wall functions is close to 1. Fully structured mesh for FSI on membrane studies were performed by Kamakoti and Shyy, (2004), Kuntz and Menter, (2004), Schroeder, (2005), Relvas and Suleman, (2006), Bletzinger et al.,