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Aerodynamic Characterization of Low Reynolds Number Flow over Fixed Wing–A Review Paper

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Abstract—*Most fascinating and least understood features of low Reynolds number flyers is their Aerodynamics. Due to the advancements in low Reynolds number applications such as Micro Air vehicles (MAV), Unmanned Air Vehicles (UAV) and wind turbines, most of the researchers concentrates on Low Reynolds number aerodynamics, transition, Laminar separation Bubble (LSB) and its effect on aerodynamic performance. This review paper is to unveil the major research activities on different aspects of Laminar Separation Bubble which has been carried out numerically, computationally and experimentally. This study is mostly concentrated on low Reynolds number transition, instability of LSB and the control of LSB.*

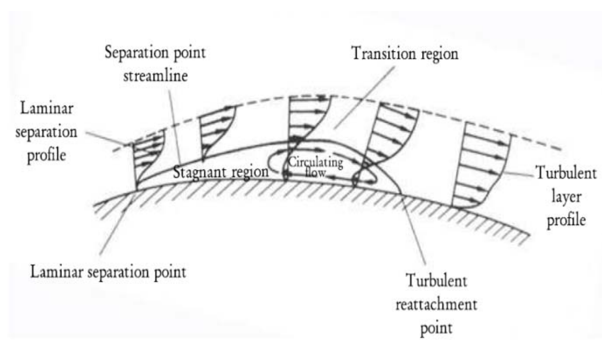
Introduction

For conventional manned aircraft wings, the Reynolds number range is of more than 10^6. The flow around the wing is typically turbulent and it doesn't separate until the aircraft reaches higher Angle of Attack as the inertia forces are dominant compared to viscous forces. In Low Reynolds number flows, the Reynolds number is of range 10^4 to 10^6. Due to the effect of viscous force, the flow which is laminar will tend to separate even in the presence of small pressure gradient. Due to the separation, there is a transition in the free shear layer near the surface and it may reattach to form laminar separation bubble (LSB). This LSB leads to decrease in aerodynamic efficiency which in turn affects the range, endurance of small scale flight such as Micro air vehicles (MAV's), Unmanned air vehicles (UAV's) and it alternatively changes the effective shape of the airfoil.

One of the earliest researches on laminar Separation Bubble is Gaster (1964). This study has been made of laminar separation bubble formed over a wide variety of Reynolds number and concluded that the structure of bubble changes with respect to Reynolds number of the separating boundary layer(Gaster,1964). In the same year, Tani (1964) observed that at relatively small angle of attack, the length of the separation bubble reduced with an increase in angle of attack until a condition reached where the "bursting" of bubble occurs. The LSB can be classified as short and long bubble. Both the bubble will degradethe aerodynamic efficiency by decreasing lift and increasing drag owing to the altered pressure distribution caused by the presence of the LSB. Formation of LSB is affected by the airfoil shape, Reynolds number, Angle of Attack, Pressure gradient, free stream turbulence, free stream disturbances and surface roughness.

Basic concept of Laminar Separation Bubble

Laminar Separation Bubble is formed due to the adverse pressure gradient and viscous effects on the surface of the airfoil. Laminar boundary layer gets separated and transition may occur in the free stream layer close to the surface and may reattach to the surface forming a LSB. There is region of recirculation in between the separation and reattachment point which is known as dead air region.



Laminar separation bubble (Lock,2007).

Due to turbulent mixing, momentum transfer eventually eliminates the reverse flow near the wall causes the LSB. This combination of separation, transition and reattachment results in laminar separation which affects the predominate effect on the entire airfoil flow field.

In other words, after laminar boundary layer separation a highly unstable detached shear layer forms and transition to turbulence takes place in the detached shear layer. The enhanced momentum transport in the turbulent flow usually enables reattachment and a turbulent boundary layer develops downstream (Saxena 2008). The Gaster (1969) study explains the stability characteristics associated with the transition taking place in separation bubble. Due to high incidence or speed, the free shear fails to reattach to the surface causing the flow to remain detached and the short bubble may burst to form long bubble, or an unattached shear layer.

From the experimental data, it is proved that the increase in Reynolds number and angle of attack decrease the length and thickness of the Laminar Separation Bubble (Mueller, 1987). As explained in the paper, the angle of attack increased making the point of laminar separation to moved forward but there is no significant change in the length of the bubble.

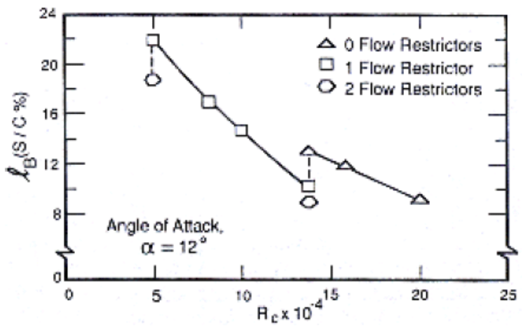


Figure 2: Total bubble length versus chord Reynolds Number

Figure 2 and 3 explains about total bubble length versus chord Reynolds number and total bubble length versus angle of attack.(O'Meara and Mueller, 1987).

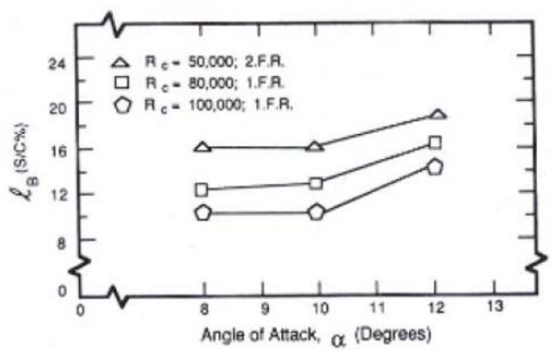


Figure 3: Total bubble length versus angle of attack.(Mueller,1987)

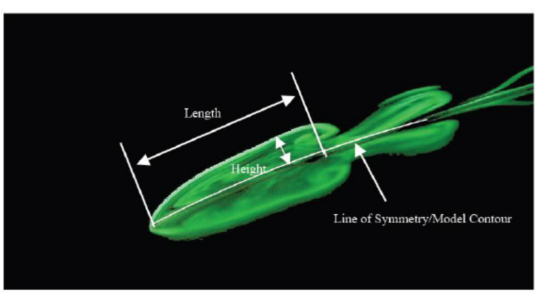


Figure 4: Measurement details of laminar separation bubble (Mohsen,2011)

The paper by Lei Juanmian (2013) concluded that at low Reynolds number, Laminar separation occurs at the both sides of the airfoil at small angle of attack. But when the angle of attack is increased, there is a formation of laminar separation bubble. At certain value of Angle of Attack, there is a formation two kinds of vortex ie. Primary and secondary vortex making the laminar separation bubble to be unstable. At first, there were lots of researches which were held in airfoils and the researches stepped one step forward continued their research even in the wing. The result of the three dimensional flow structures showed that there is significant influence on the delay of forming LSB. The LSB expands chord wise downstream and span wise outboard. There is a strong wing tip vortex forming at the end of the span and at higher angle of attack it comes inboard to affect the lift and decreased the drag.

There are numerous researches on laminar separation bubble showing the incapability or the reason for laminar separation bubble. But there is disturbances inwhich occurs on or after the LSB which causes the instability of LSB is yet to be uncovered.

Instability of bubble

Investigations of disturbances developed in LSB are investigated by Haggmark (2000) using wind tunnel experiment in controlled forcing of low amplitude instability waves. There is a local disturbance in the velocity profile at inflection showing the inviscid type of instability.

A detailed experimental and theoretical investigation of the linear instability mechanisms associated with a laminar separation bubble has been performed by Diwan and Ramesh (2009). In this study, it has been showed that the primary instability mechanism is inviscid inflectional in nature, and its origin can be traced back to upstream of separation.

Through reverse flow visualization with the reduced frequency k=1, there is a combination of first and second trailing edge vortices forming in to mushroom shaped vertical structures in the near wake region(Dong-Ha kim, 2014).

Recent researches were held in the interaction between laminar to turbulent transition and the wake of an airfoil by A.Ducoin, 2016. The transition is investigated by using DMD (Dynamic Mode Decomposition) is used in order to extract the main physical modes of the flow and to highlight the interaction between the laminar and turbulent transition.

Control of Laminar Separation Bubble

Boundary layer control was first introduced by Prandtl (1904). . LSB are widely characterized as parasitic as they increase drag which in turn reduces the aerodynamic efficiency (Aholt, 2009). Still there are many researches who work on eliminating the LSB by using control methods. Flow control methods can be categorized in to two main types namely active and passive flow controls methods. Active flow control method can be initialized by adding energy to the flow field or boundary layer directly. Passive flow control method can be done by changing the surface roughness or geometrical discontinuities. Some of the passive control are even being used in high Reynolds number flows such as vortex generators, slats etc. But the passive flow controls are used but they have their own disadvantages. As the passive flow control are generally creating turbulence regardless of necessity. (Rist and Augustin, 2006; Bak et al., 1999). Regardless of the disadvantages, active method is considered. Active flow control methods such as pneumatic turbulators and plasma actuators are of current research interest (Aholt and Finaish, 2011). Most oftenly used active methods are blowing, suction, acoustic excitation and mems, etc. There is lot research going on in the control methods of laminar separation bubble.

For rigid airfoils plunging with small-amplitude, two mechanismsof lift enhancement have been identified: deflected jets and convected LEVs. Stable deflected jets form at high Strouhal numbers for pre-stall angles of attack. Deflected jets are caused by pairing of the clockwise and counter-clockwise TEVs to form dipoles. These dipoles are asymmetric in position and strength and therefore self-advent at an angle to the free stream creating asymmetry in the flow field. (I.Gursul, 2014). These are used to control the LSB.

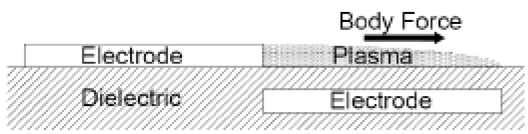


Figure 5: Plasma actuator

Conclusion

This paper showed few result studies carried out in the laminar separation bubble, basic concepts and characteristics, instability of LSB and control methods of Laminar Separation Bubble. According to the researches so far, there is complete understanding of influence of adverse pressure gradient in the Laminar Separation Bubble both experimentally and numerically. But still there is a lack of understanding physical phenomena occurring in the laminar separation bubble and transition region. In regard to recent works on laminar-turbulent transition, it appears that some efforts are still to be done in (i) the characterization of the transitional region and its direct effect on loading (i.e.on pressure distribution hydro/aerodynamic loading (i.e. global effects) and (ii) the understanding of the physical mechanisms that lead to turbulence, including the instability mechanisms and the unsteadiness of the vortex flow that convects downstream of the transitional region and later in the wake. This literature review will pay a way to the main research where the objective isto study the laminar separation bubble by experimentally, computationally and analytically by changing various parameters such as

- NACA series 0012 and 4412
- Wing chord 150 and 250 mm
- Velocity range (5,8,12 m/s)

To study about the physical mechanism that leads to turbulence, including instability mechanism which occurs during the transition. To control the LSB by using flow controls

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