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Laminar Separation Bubble: Its Structure, Dynamics and Control

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Abstract

Due to the importance of drag reduction in various air and ground vehicles, gas turbines, etc., and since presence of separation bubbles play the key role in this context, the main aim of this review work is to uncover the major research activities on different aspects of laminar separation bubble (LSB) which have been carried out theoretically and experimentally for past few decades. These research studies are majorly concentrated on: structure, characteristics and dynamics of LSB; instability of LSB; and most important issue of controlling LSB passively and actively.

Introduction:

For conventional aircraft wings, whose Reynolds number exceeds a million, the flow is typically turbulent with the boundary layer able to strengthen itself by 'mixing'. Consequently flow doesn't separate until high angles of attack are encountered. For lower Reynolds numbers, the flow is initially laminar and is prone to separate even under mild adverse pressure gradient. Under certain flow conditions, the separated flow reattaches and forms a Laminar Separation Bubble (LSB) while transitioning from laminar to turbulent state. Laminar separation bubble could modify the effective shape of the airfoil and consequently influence the aerodynamic performance, generally in a negative manner.

The need to understand low Reynolds number (10^4 to 10^6) aerodynamics is driven by variety of applications from windmills to aircrafts. High Altitude Long Endurance (HALE) Reconnaissance aircrafts, Micro Aerial Vehicles, insect and bird's flight fall in this Reynolds number range (Saxena, 2009).

Usually, under the influence of an adverse pressure gradient, a laminar boundary layer separates from the surface, becomes transitional and ultimately the separated shear layer reattaches to form a 'laminar separation bubble'. Such bubbles are typically observed close to the leading edges of thin aerofoils, on gas turbine blades and on low Reynolds number micro-aero-vehicle wings (Diwan and Ramesh, 2007). Presence of bubbles has a deteriorating effect on the performance of the device. The understanding of the physics of the laminar separation bubble and possible ways to control it thus are essential prerequisites for efficient design of these aerodynamic devices.

One of the earliest surveys of the literature was that of Tani (1964). Most of the work reported therein was done on the suction surface of a variety of aerofoil configurations at different angles of attack. It was observed that at relatively small angles of attack, the length of the separation bubble reduced with an increase in angle of attack till a critical condition was reached when there was a sudden increase in the length of the bubble. This phenomenon was termed 'bursting' of the bubble, and most of the early work was done towards devising empirical criteria to predict bursting, since it was seen to be directly related to the stalling of the aerofoil (Diwan and Ramesh, 2009).

Gaster (1969) was the first to systematically explore the stability characteristics associated with the transition taking place in separation bubble. Many recent studies have been directed towards exploring the dynamics of separation bubbles (see Watmuff, 1999; Pauley et al., 1990; Marxen et al., 2003). The bubble constitutes, at the same time, laminar separation, transition to turbulence and aspects of both the attached as well as free shear layer. Even though there is a fair amount of understanding of the individual aspects, the interplay amongst them is far from being understood (Diwan and Ramesh, 2007).

Separation bubbles are important due to the controlling influence that they can have on the overall performance of aerofoils. Leading edge separation bubbles do not greatly influence the pressure distribution but effectively fix the location of transition to turbulence (Sandham, 2008). Additionally, short bubbles may undergo a bursting process which fixes the maximum lift that can be generated by an aerofoil. Since the early observations of Jones (1934), much work has been done to study transitional separation bubbles in the laboratory and more recently by direct numerical simulation, with a result that much of the flow physics has been identified, if not yet fully incorporated into prediction methods. The pioneering experiments covered in the PhD theses of McGregor (1954), Gaster (1963), Young and Horton (1996), Horton (1968), Woodward (1970) and the more recent direct numerical simulations (DNS) of Alam (1999) have discovered a lot of unknown aspects of separation bubbles.

In this report, an effort is made to make a review on earlier works with emphasis on dynamics and control of separation bubbles. But, before discussing experimental and modelling techniques in this regard, the physical concept of LSB is explained.

Basic concepts:

A laminar separation bubble is formed when the previously attached laminar boundary layer encounters an adverse pressure gradient of sufficient magnitude to cause the flow to separate. Downstream of the point of separation, denoted by S in Figure 1 (O'Meara and Mueller, 1987), the flow can be roughly divided into two main regions. The first region is bounded by the mean dividing streamline ST'R and the airfoil surface. The mean dividing streamline is generally regarded as the collection of points across each velocity profile at which the integrated mass flow is zero. This first region represents the relatively slow re-circulatory flow forming the bubble.

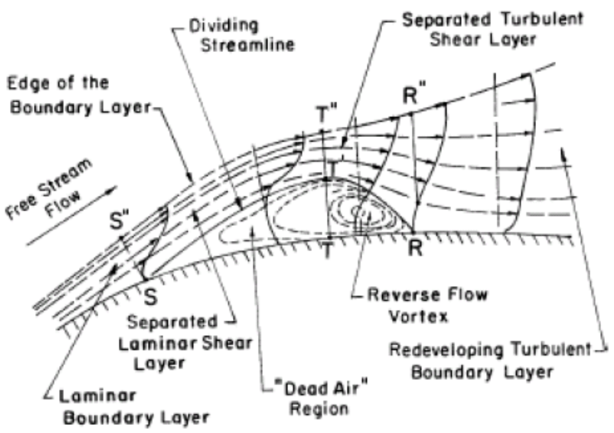


Figure 1: Laminar Separation Bubble

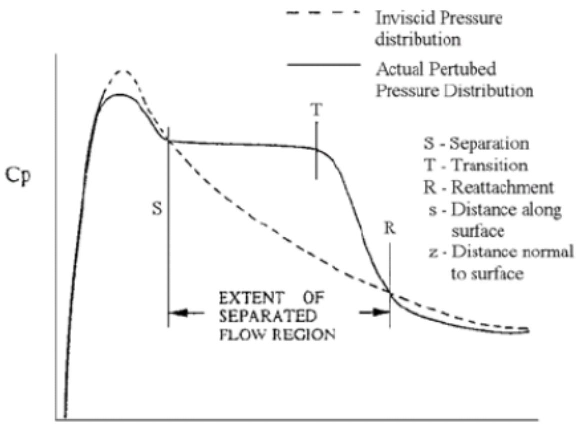


Figure 2: C_P distribution on top surface

The second region of flow consists of the free shear layer contained between the outer edge of the boundary layer S"T"R" and the dividing streamline. This separated shear layer undergoes transition at a location denoted by T due to disturbance amplification occurring in the unstable laminar layer. Momentum transfer due to turbulent mixing eventually eliminates the reverse flow near the wall and the flow reattaches at point R. This process of separation, transition and reattachment results in a laminar separation bubble that has a predominate effect on the entire airfoil flow field. As the Reynolds number decreases, the viscous damping effect increases, and it tends to suppress the transition process or delay reattachment (Saxena, 2009).

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. In the time-averaged picture there is a 'deadair' region under the detached shear layer immediately after separation and a strong recirculation zone near the rear of the bubble (Sandham, 2008).

The effect of a laminar separation bubble on an airfoil pressure distribution is demonstrated in Figure 2 which shows an experimentally measured distribution plus a pair of theoretically predicted distributions: one with and one without the bubble (Lee et al., 2006). Once the flow separates, the edge of the bubble becomes a zero pressure gradient streamline which is evidenced by the plateau in the pressure distribution (Saxena, 2009). Note that downstream of the bubble (after re-attachment) the flow appears to proceed normally and fully attached to the trailing edge.

Another interpretation on creation of separation bubble made by Gaster (1969) is that, the laminar boundary layer over the nose of a thin aerofoil at high incidence fails to remain attached to the upper surface in the region of high adverse pressure gradient that occurs just downstream of the suction peak. The separated shear layer which is formed may curve back to the aerofoil surface to form a shallow region of reverse flow known as a separation bubble. The fluid is static in the forward region of the bubble and a constant pressure region results. At high Reynolds numbers the extent of such a bubble is exceedingly small, of the order of 1 per cent chord, and the slight step in the pressure distribution produced by the dead air region has a negligible effect on the forces acting on the aerofoil. However, with a change in incidence or speed (usually an increase of incidence or a reduction in speed) the shear layer may fail to reattach and the 'short' bubble may 'burst' to form either a 'long' bubble, or an unattached free shear layer. This change in mode of reattachment can occur gradually or quite sharply, depending on the type of aerofoil. The pressure-distribution association with a long bubble is quite different from that of inviscid flow, and the forces acting on the aerofoil are therefore modified, sometimes quite drastically, by the change in mode of reattachment. In particular, bubble bursting creates an increase in drag and an undesirable change in pitching moment. If a very large bubble is formed on bursting, or if the shear layer fails to reattach, there is also an appreciable fall in lift. This is one type of stall the thin aerofoil nose stall.

General characteristics of separation bubble:

From experimental data it is found out that, variables that significantly affect the physical dimensions of the separation bubble are Reynolds number, external disturbance and the angle of attack (Shyy et al., 2008). Figure 3 shows the effect of Reynolds number for various levels of freestream disturbances (O'Meara and Mueller, 1987). The length of the bubble decreases as the Reynolds number is increased. The effect of freestream disturbance on the bubble length is that, as the disturbance level is increased, the bubble is reduced in length and the suction peak grows in magnitude. This phenomenon closely resembles the effects observed by increasing the Reynolds number and are often equated. The effect of angle of attack variation is summarized in Figure 4 (O'Meara and Mueller, 1987). As the angle of attack is increased, the point of laminar separation moved forward but there is no significant change in the length of the bubble. The forward movement of the separation point with increase in angle of attack is due to more severe pressure gradient occurring at higher incidences.

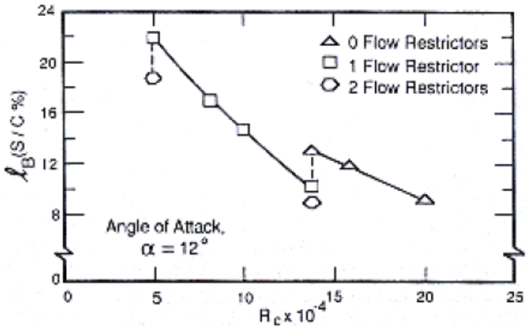
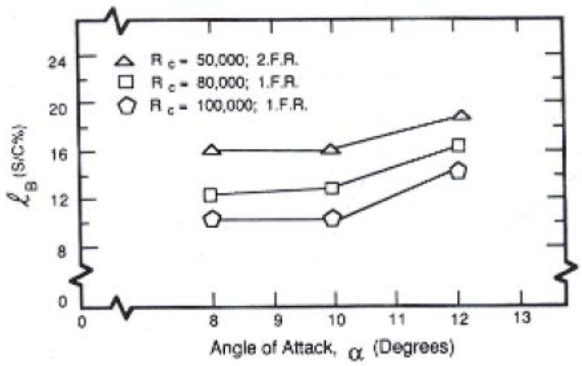


Figure 3: Total bubble length versus chord Reynolds Number.

In addition to overall length, the thickness of the bubble is also influenced by these parameters and Figure 5 shows the variation of bubble height with Reynolds number (O'Meara and Mueller, 1987). The figure indicates sharp reduction in bubble thickness with increase in chord Reynolds number.



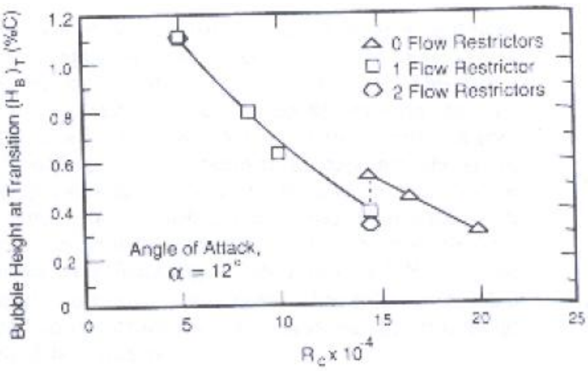


Figure 4: Total bubble length versus angle of attack. Figure 5: Bubble height variation.

Experiments carried out by Diwan and Ramesh (2007) showing that both length and height of the bubble increase with decrease in speed. However, further analysis shows that the height increases at a greater rate than the length. This feature could be useful in characterising separation bubbles, especially from the point of view of low Reynolds number aerofoil design. Figure 6 shows a typical smoke flow visualisation picture of their experiments. The Reynolds number based on the freestream velocity and the momentum thickness at separation was calculated to be 551·4.

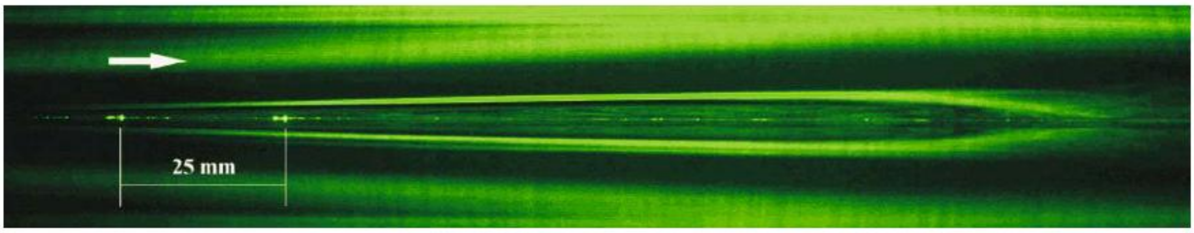


Figure 6: A typical smoke flow visualisation picture depicting the separation bubble. The flow is from left to right. Also visible is the reflection of the bubble in the polished surface of the plate.

An investigation into the laminar separation bubble that frequently plagues airborne vehicles operating in the low Reynolds number regime is made by Swift (2009). A basic generic model was chosen for this investigation: a circular arc (section of 16 inch diameter PVC pipe) with sharp leading and trailing edges having a chord length of 9.3 inches and height of 1.5 inches (see

Figure 7). Small diameter cylinders were then statically placed upstream of the model to determine their interaction with the laminar separation bubble and its effects on the boundary layer downstream over the airfoil model. The length and height of the laminar separation bubble (Figure 8) was found to be impacted with a small cylindrical wire placed upstream at all Reynolds numbers and angles of attack with the exception of an 18 degree angle of attack at the higher Reynolds number. However, these changes did not result in a substantial or distinguishable improvement in the downstream separation point. The laminar separation bubble was found to be nearly or completely eliminated when a thermocouple wire was placed upstream of the leading edge. Although the elimination of the bubble would result in only a minor decrease in drag and increase in lift, there would be a possible improvement in the stability of the leading edge stall and possible reduction or elimination in the hysteresis associated with stall.

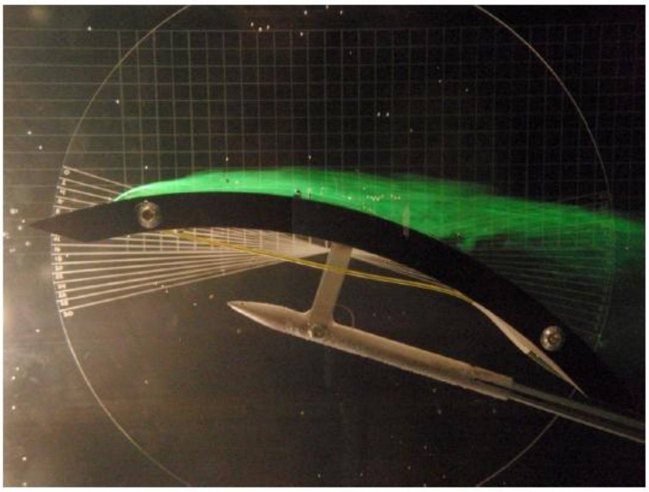


Figure 7: Two Dimensional View of Model With Endplates and Mounting Mechanism.

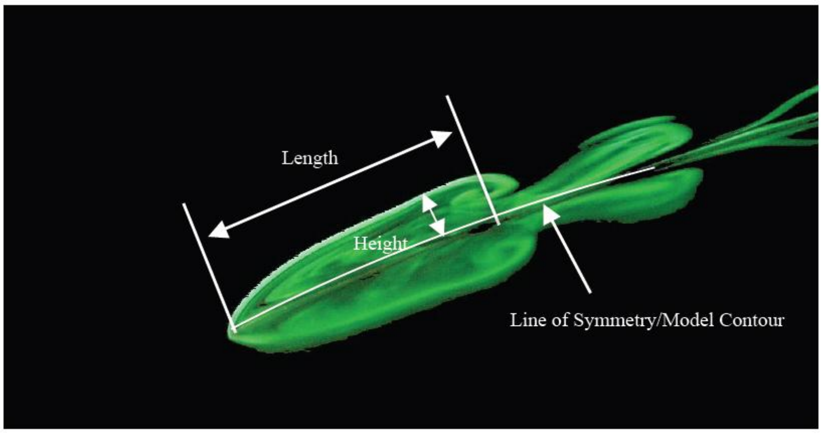


Figure 8: Measurement Details of the Laminar Separation Bubble.

In fact the dependency of separation bubble on Reynolds number was first found by Gaster (1969). The study has been made of laminar separation bubbles formed over a wide range of Reynolds numbers and in a variety of pressure distributions. His final conclusion was that, the structure of the bubble depended on the value of the Reynolds number of the separating boundary layer and a parameter based on the pressure rise over the region occupied by the bubble. Conditions for the bursting of 'short' bubbles were determined by a unique relationship between these two parameters.

Instability of laminar separation bubble:

Investigations of disturbances developing in a laminar separation bubble flow has been studied by Häggmar (2000) in wind tunnel experiments using controlled forcing of low-amplitude instability waves. A region with exponential disturbance growth is observed in the separated shear layer associated with a highly two-dimensional flow. A local maximum in the disturbance amplitude develops at the inflection point in the mean velocity profile, indicating an inviscid type of instability. Further downstream, in the reattachment region, a complex three-dimensional flows structure develops including reverse flown ear the wall.

The occurrence of temporally growing unstable disturbances is investigated by Rist and Maucher (2002) based on eigenvalues with zero group velocity from linear stability theory (LST) and compared with observations of upstream travelling disturbances obtained in a two-dimensional direct numerical simulation (DNS) of an unsteady laminar separation bubble. For large wall distances two unstable modes are found. Apart from a low-frequency motion of the bubble the DNS exhibit high-frequency oscillations which periodically appear and disappear. Part of these disturbances travel upstream and amplify with respect to time. Their initial occurrence and their frequency are in excellent agreement with the results of the parameter study based on LST and a closer examination of the disturbances yields insight into their spatial structure. Figure 9 shows integration domain and free-stream velocity for their DNS calculation.

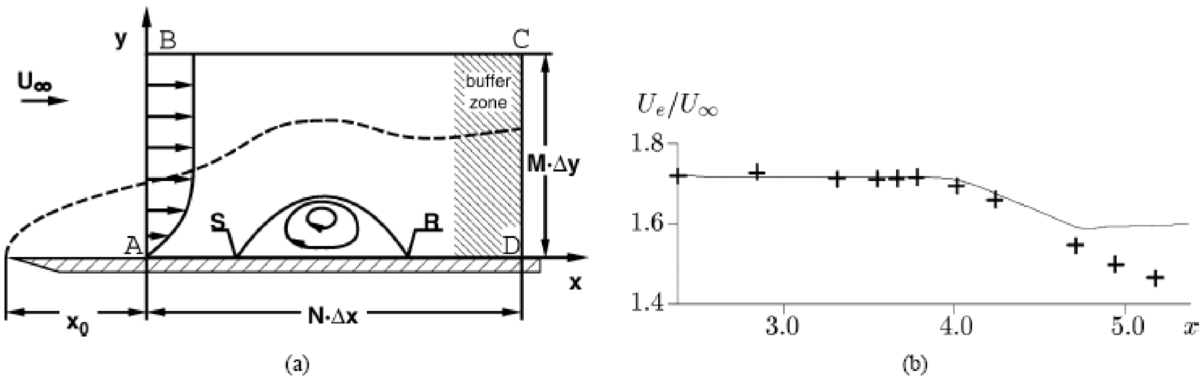


Figure 9: Integration domain (a) and free-stream velocity (b) for the DNS of a laminar separation bubble. S = separation point, R = reattachment point; experimental measurements with tripped boundary layer (+) for comparison.

Recently, 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). It has been shown that the primary instability mechanism in a separation bubble, in the form of two-dimensional waves, is inviscid inflectional in nature, and its origin can be traced back to the region upstream of separation. In other words, the inviscid inflectional instability associated with the separated shear layer should be logically seen as an extension of the instability of the upstream attached adverse-pressure-gradient boundary layer. This modifies the traditional view that connects the origin of the inviscid instability in a bubble to the detached shear layer outside the bubble with its associated Kelvin–Helmholtz mechanism. Also, a scaling principle for the most amplified frequency in terms of the height of the inflection point from the wall (y_{in}) and the vorticity thickness (δ_ω) is obtained and shown it to be universal, independent of the precise shape of the velocity profile. This was motivated by the linear inviscid spatial stability analysis of a piecewise linear profile adjoining a solid wall. It is shown that only when the separated shear layer has moved considerably away from the wall (and this happens near the maximum-height location of the mean bubble), a description by the Kelvin–Helmholtz instability paradigm, with its associated scaling principles (such as ω^*=0.21), could become relevant.

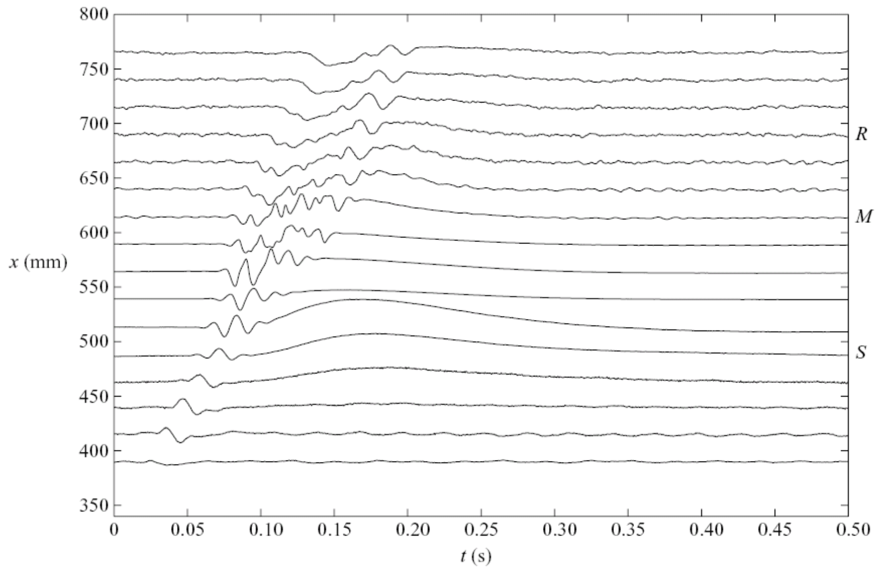


Figure 10: Evolution of the wave packet in the downstream direction. The disturbance is introduced at x=340mm; S, M and R indicate separation, maximum-height and reattachment locations for the unexcited case respectively; U_{ref} =2.78ms^{-1}.

The evolution of wave packet in the downstream direction is shown in Figure 10 (Diwan and Ramesh, 2009). This figure suggests that the inflectional instability does indeed originate upstream of the separation location, and it is advected downstream to manifest as the inviscid instability of the inflectional profile associated with the separation bubble.

BiGlobal linear analysis provides a unified means of addressing instability phenomena of separated flows in complex configurations. It has been demonstrated (Theofilis et al., 2004)) that, closed separation bubbles sustain global eigenmodes distinct from the known inflectional instability of the shear-layer in three case-studies of canonical flat-plate and complex airfoil and low-pressure turbine flows. In all three applications and parameter ranges studied, a consistent picture emerges regarding the characteristics of the respective most amplified/least damped global mode; the latter is found to have analogous characteristics in terms of frequency and spatial structure of the respective disturbance eigenfunctions in the different applications. The dominant global mode of laminar separation remains less significant than other types of linear instabilities in all three applications, but its omission would result in an incomplete description of the phenomenon of laminar separated flow instability or efforts to reconstruct and control the respective flow fields using reduced-order models.

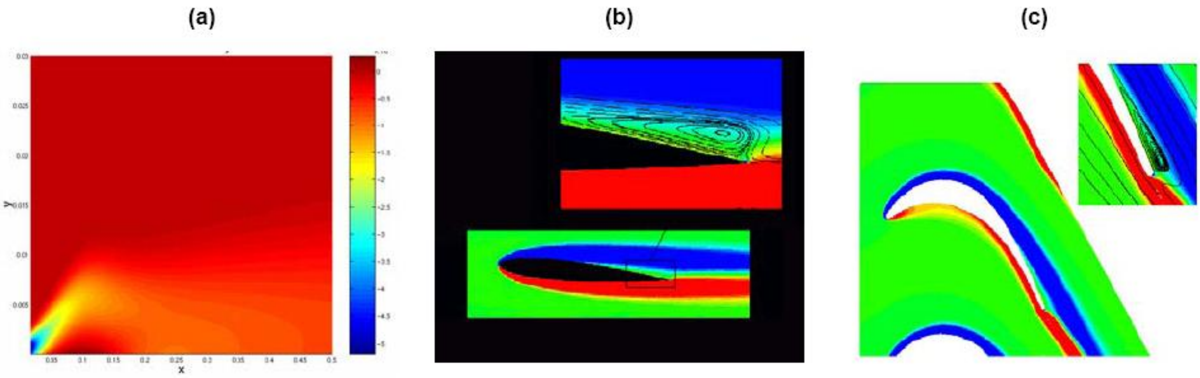


Figure 11: Basic flow vorticity in (a) the flat plate (Theofilis et al., 2000), (b) the NACA 0012 airfoil at an angle of attach (Theofilis and Sherwin, 2001; Theofilis et al., 2002) and (c) the T-106/300 Low Pressure Turbine blade (Abdessemed et al., 2004).

In case studies of separated flows carried out by Theofilis et al., (2004), it is seen that, despite the different means of producing separation, in all three cases steady closed separation bubbles have been obtained (see Figure 11).
The instability of nominally laminar steady two-dimensional closed separation bubbles is investigated using direct numerical simulations and BiGlobal instability analysis (Simens et al., 2006). They demonstrate that large steady two-dimensional bubbles may become unsteady and shortened in the mean upon applying periodic forcing. Using BiGlobal instability analysis, it is shown that, the generation of Kelvin-Helmholtz instabilities as solutions of the pertinent partial-derivative eigenvalue problem, without resorting to the simplifying assumptions on the form of the underlying basic state is possible.
Another research studies on instability of laminar separation bubbles is carried out by a team from School of Aeronautics, Universidad Politécnica de Madrid. Global linear modal instability analysis of laminar separation bubble flows has been performed (Rodríguez et al., 2010). The pertinent direct and adjoint eigenvalue problems have been solved in order to understand receptivity, sensitivity and instability of the global mode associated with adverse-pressure-gradient-generated LSB, as well as that formed by shock/boundary-layer-interaction (SBLI) and over a finite angle wedge in supersonic flow (see Figure 12). In incompressible flow the global mode of LSB has been found to be at the origin of the experimentally-observed phenomena of U-separation and stall-cell formation. Qualitatively analogous results have been obtained in compressible subsonic flow, but convergence of the corresponding eigenspectra in supersonic flow continues posing computational challenges, despite use of state-of-the-art algorithms and the largest European supercomputing facility.

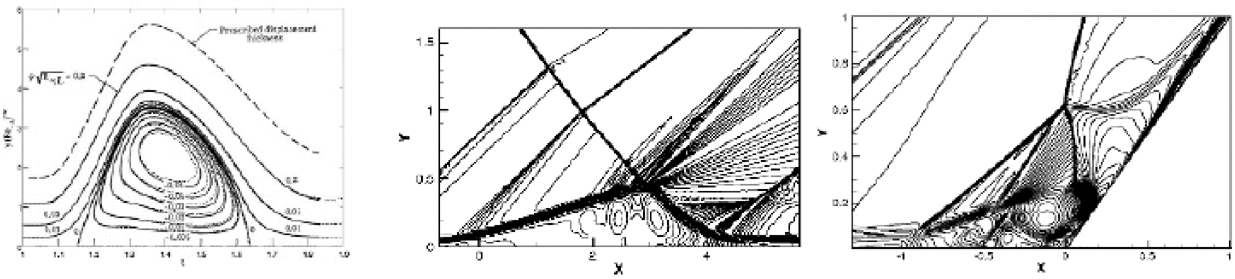


Figure 12: Isolines of stream function in incompressible LSB flow (Rodríguez and Theofilis, 2009) (left). Isolines of density for compressible LSB flows generated by SBLI (middle) and a 45 degree wedge (Ekaterinaris, 2004) (right).

Same research group at Madrid, Spain (Theofilis et al., 2010) somewhere else on global instability of laminar separation bubbles concluded the followings:
1. In the past few years, global linear instability of LSB has been revisited, using state-of-the-art hardware and algorithms.
2. Eigenspectra of LSB flows have been understood and classified in branches of known and newly-discovered eigenmodes.
3. Major achievements:
- World-largest numerical solutions of global eigenvalue problems (EVP) are routinely performed
- Key aerodynamic phenomena have been explained via critical point theory, applied to global mode results
4. Theoretical foundation for control of LSB flows has been laid.
5. Global mode of LSB at the origin of observable phenomena:
- U-separation on semi-infinite plate
- Stall cells on (stalled) airfoil
6. Receptivity/Sensitivity/AFC feasible (practical?) via:
- Adjoint EVP solution

• Direct/adjoint coupling (the Crete connection)
7. Minor effect of compressibility on global instability in the subsonic compressible regime.
8. Global instability analysis of LSB in realistic supersonic flows apparently quite some way down the horizon.

Laminar separation bubble control:

LSBs are widely regarded as parasitic because they typically have the effect of increasing drag, thus reducing aerodynamic efficiency (Aholt, 2009). Additionally, LSBs are characteristically sensitive to small fluctuations in upstream flow characteristics, and are consequently prone to instability (Rist and Augustin, 2006; Zaman and McKinzie 1989; Bak et al., 1999). This instability results in design uncertainty, and has been experimentally observed to reduce aerodynamic performance as well as result in potentially dangerous dynamic structural loading in aerospace structures (Bak et al., 1999; Schreck and Robinson, 2007). Consequently, methods of controlling or eliminating LSBs are a priority of many aerodynamicists. The most effective methods of LSB elimination currently in use involve forcing premature turbulent transition of the boundary layer, making it less likely to separate; e.g. careful airfoil selection or the placement of mechanical turbulators upstream of the laminar separation point (Rist and Augustin, 2006; Bak et al., 1999). However, such methods are typically passive, generating turbulence regardless of necessity. In applications where a system must perform under a wide range of operating conditions (such as a UAV or wind turbine), an active control system is desirable. It is for this reason that flow control systems such as pneumatic turbulators and plasma actuators are of current research interest (Aholt and Finaish, 2011).
As mentioned by Augustin et al., (2004), existing systems to avoid the formation of LSBs involve the generation of turbulence upstream of the separation. Most often used turbulators apply zigzag or dimple tape mounted on the surface of the airfoil. Other devices use vortex generators (Kerho et al., 1993) or constant blowing of air through holes in the surface of the airfoil (Horstmann et al., 1984) to generate-large scale streamwise vortices. For such active blowing devices a complicated system to provide the necessary bleed air might be necessary. All these systems have in common that they have to be developed for an optimum design point. Therefore, these systems cannot capture off-design conditions like different speed tasks of sail planes optimized for thermal flights. Active-blowing devices can be switched off at off-design conditions, but nevertheless additional disturbances may be generated by secondary flow through the holes in the presence of pressure gradients in the spanwise direction of the airfoil. Active systems which deform the surface of the airfoil to introduce disturbances into the flow represent a solution to these problems. Switched off, these systems would no longer be a source of additional drag. As a drawback these systems only provide very small deformation amplitudes and imply electric driving and control devices. Moreover, a complex integrated sensor, controller and actuator system becomes desirable to become independent of any external interference with the system by the pilot. As maximum efficiency is the aim, according active turbulators have to be low-energy consuming and thin layered to fit into the limited space available on an airfoil besides the required supporting structural components. Nevertheless, such surface-mounted active devices can generate high-frequency perturbations which are necessary to introduce Tollmien-Schlichting-type boundary-layer disturbances into the flow. Due to hydrodynamic instability of the LSB flow, these boundary-layer disturbances become strongly amplified which leads to laminar-turbulent transition despite of their low initial disturbance amplitude. By introducing boundary-layer perturbations at a disturbance strip upstream of the separation into the laminar flow, transition can be triggered and therefore the size of the LSB be influenced.
In the work carried out by Augustin et al., (2004), LSB flows are investigated in detail by means of linear stability theory (Reed et al., 1996) and direct numerical simulations (DNS) to evaluate methods using disturbance modes with different excitation parameters with respect to their impact on the size of typical mid-chord LSBs under different adverse pressure gradients. Their results show the advantages of the excitation of unsteady 2-d or 3-d disturbances rather than

steady disturbances in separation control scenarios. In order to provide the necessary unsteady disturbance amplitude, a possible control system for LSBs would consist of a frequency generator, an amplifier and an actuator (see Figure 13), as already discussed in (Augustin et al., 2003), mainly because it suffices to provoke laminar-turbulent transition by some appropriate means without an urgent need for some highly sophisticated controller. In fact, a simple switch that turns LSB control on or off when appropriate could be sufficient, once the different flow situations are understood well enough. As already shown in (Augustin et al., 2003) the frequency generator could be replaced by a feed-back of instantaneous skin friction signals obtained from a position downstream of the separation bubble. The broad band of frequencies in the most unstable frequency range due to hydrodynamic instability then provides a robust signal source for the actuator, after an appropriate reduction to lower amplitudes.

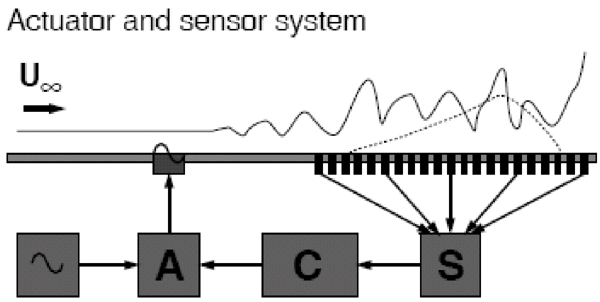


Figure 13: Sensor (S)-actuator (A) concept with controller (C) and signal generator (~).

In another attempt, control of flow over a NACA2415 aerofoil which experiences a laminar separation bubble at a transitional Reynolds number of 2×10^5 is computationally investigated using blowing or suction (Genç and Kaynak, 2009). In the computational results, the blowing/suction control mechanism appears to be the suppression of the separation bubble and the reduction of the upper surface pressure coefficients to increase lift and decrease the drag (see Figure 14). Furthermore, the smallest blowing results are better larger blowing velocity ratios independent of the blowing locations while the largest suction results are better smaller suction velocity ratios independent of the suction jet locations.

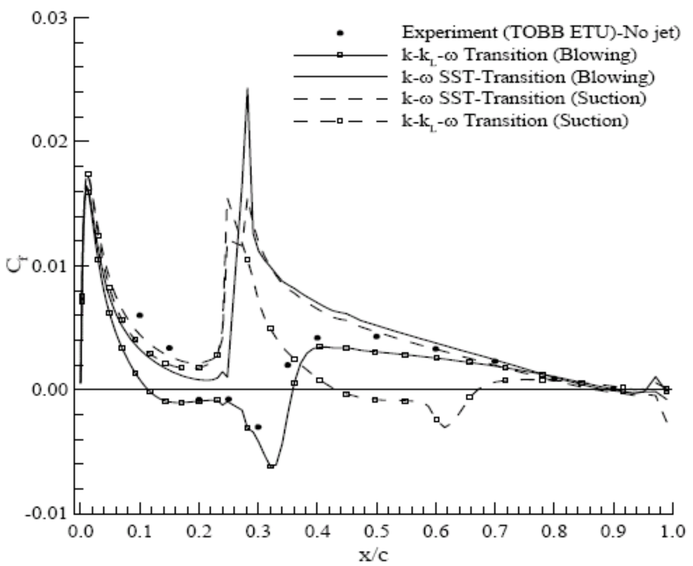


Figure 14: Comparison of numerical and experimental C_f for the NACA 2415 aerofoil without and with blowing/suction at $\alpha = 8°$.

Control of trailing-edge separation by tangential blowing inside the bubble has been investigated by Viswanath and Madhavan (2004).

In the classical boundary layer control approach, the boundary layer is energised upstream or ahead of the separation location (Figure 15a). Viswanath et al., (2000) demonstrated recently through detailed flow-field measurements in an axisymmetric separated flow that injection or blowing downstream of separation, but inside the bubble (Figure 15b) can be an effective means of separation control.

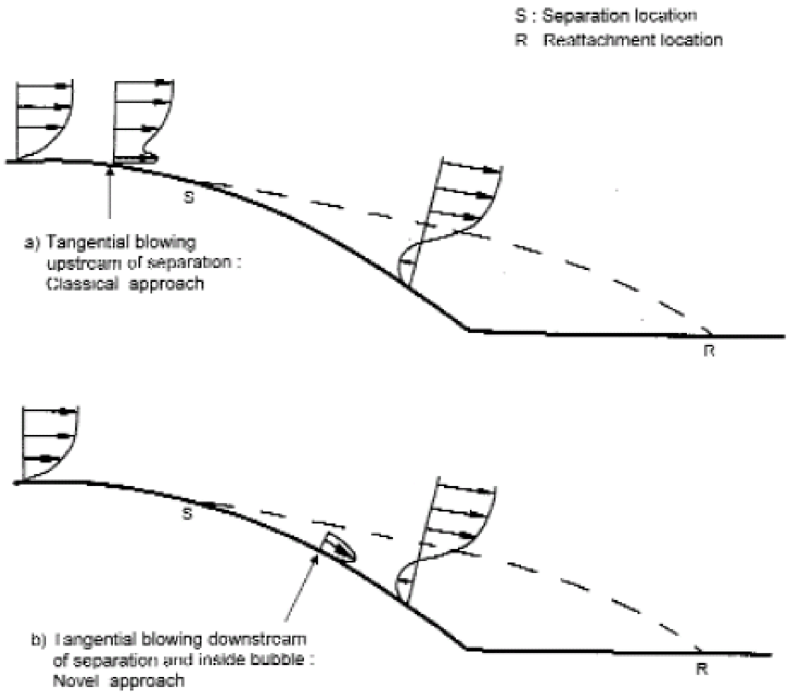


Figure 15: Schematic of tangential blowing concepts for separation control.

Their results show that, with the novel approach of blowing inside the bubble, it is the flow in the bubble (or dead air zone) which is energised leading to the eventual removal of shear layer closure, as opposed to energisation of the boundary-layer upstream of separation point, which is adopted in classical boundary-layer control (Jahanmiri, 2010). Manipulation of shear layer reattachment or closure is the 'Key Principle of Separation Control'. The flow mechanisms that may be responsible for the effectiveness of this blowing concept include:
(a) elimination of wall flow reversal due to the interaction of the injected jet (having higher total pressure or longitudinal momentum) with the reversed flow boundary-layer leading to surface pressure recovery;
(b) injection of mass into the bubble causes a strong mass imbalance affecting the shear layer entrainment characteristics ; and
(c) jet entrainment of the reversed flow in the bubble, a strong factor promoting increased mixing near the wall.
Correa et al., (2010) used an acoustic source to control the size and location of the laminar separation bubble on a FX63-137 airfoil. Their results showed that, acoustic excitations were able to reduce the bubble size by amplifying KH and TS instabilities, but it was not possible to achieve a bubble breakdown. However, an acoustic source with localized effects may be a potential candidate to reduce the bubble size in practical applications.
As an active flow control strategy of laminar separation bubbles developed over subsonic airfoils at low Reynolds numbers, Aholt and Finaish (2011) made a computational parametric study to examine the plausibility of an external body force generated by active means, such as a plasma actuator (Figure 16). In this study, the effects of altering the strength and location of the "actuator" on the size and location of the LSB and on the aerodynamic performance of the airfoil were observed. It was found that the body force, when properly located and with sufficient

magnitude, could effectively eliminate the LSB (see Figure 17). Additionally, it was found that by eliminating the LSB, the aerodynamic efficiency of the airfoil could be improved by as much as 60%.

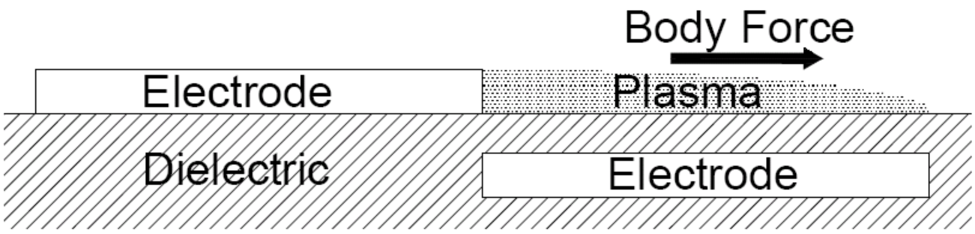
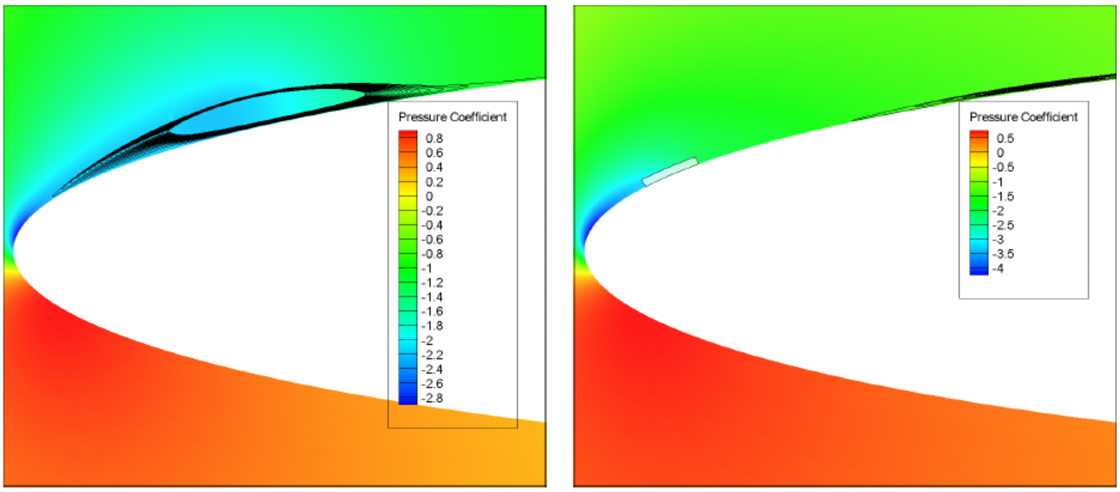


Figure 16: Potential approach of external force generation: Plasma actuator (cross-section).



(a) $f_{nd} = 0$ (reference case) (b) $f_{nd} = 20$, $X_s = 0.0119$

Figure 17: Comparison between stream traces and pressure coefficient contour plots for control case and optimal performance case.

Control of laminar separation using zero-net-mass-flux (ZNMF) devices for airfoils operating at low to medium Reynolds numbers is a common approach in laboratory experiments, in both numerical (e.g., Fasel & Postl, 2006; Rist & Augustin, 2006) and experimental (e.g., Bons et al., 2001) setups. However, ongoing physical processes in such flows can be diverse, spanning from convective-type (Kelvin-Helmholtz) instability (Rist & Augustin, 2006) to vortex-wall interaction (Simens & Jimenez, 2006). Marxen et al., (2006) made an numerical evaluation of active control of a laminar separation bubble in terms of local linear stability theory based on the Orr-Sommerfeld equation. Such an instability corresponds to the convective-type Kelvin-Helmholtz instability for laminar separation bubbles. The general setup (Figure 18) is given by a finite flat plate with an elliptic nose placed in a channel with slip walls, subject to a uniform incoming free-stream at the channel inlet. In the rear part of the plate, steady blowing and suction is applied on the upper (slip) wall of the channel in the interval 0.2<x/c<0.8, which induces an adverse pressure gradient at the top wall of the at plate and in turn leads to separation of the laminar boundary layer on that plate. A ZNMF actuator is centered at x/c=0.625. This actuator is used to diminish boundary layer separation downstream of its location by forcing at different frequencies, but with a fixed amplitude.

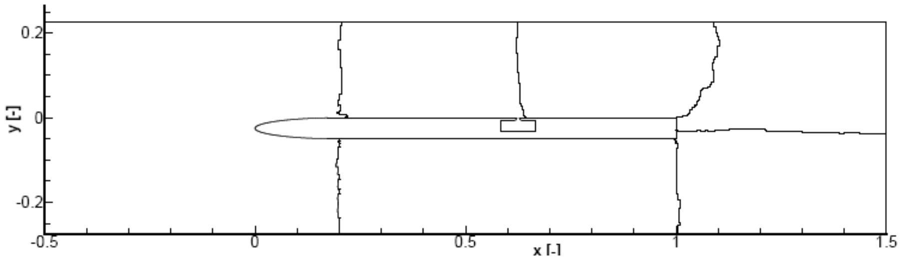


Figure 18: Configuration used for numerical simulations.

Their result indicates that a larger separation bubble corresponds to a larger region of instability and a higher most-amplified frequency. A feedback effect of the mean flow deformation, i.e., a change of the mean flow caused through disturbance input even upstream of transition, could be observed in accordance with reports in Marxen (2005). A deeper understanding of flow dynamics for the present case of laminar-separation control was gained with the help of linear stability theory.
Behavior of the separation bubble on the suction surface of a compressor or a turbine blade has been attracting attention of researchers and designers of turbomachines for several decades because the separation is closely related to efficiency, stability, heat transfer and noise generation encountered in turbomachines (see Jahanmiri, 2011). In this regard, much effort is devoted to studies of a leading edge separation bubble. An attempt is made by Funazaki et al., (2000) to suppress a blade leading edge separation bubble by utilizing a stationary bar wake. This study aims at exploration of a possibility for reducing the aerodynamic loss due to blade boundary layer that is accompanied with the separation bubble. The test model used in this study consists of semi-circular leading edge and two parallel flat plates. It can be tilted against the inlet flow so as to change the characteristics of the separation bubble. Emphasis in this study is placed on the effect of bar shifting or bar clocking across the inlet flow in order to see how the bar-wake position with respect to the test model affects the separation bubble as well as aerodynamic loss generated within the boundary layer (see Figure 19). The present study reveals a loss reduction through the separation bubble control using a properly “clocked” bar wake by choosing a proper position of the bar against the model.

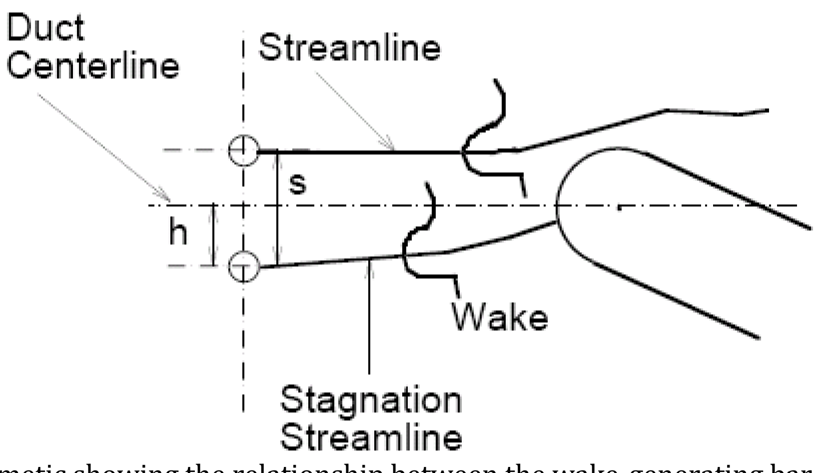


Figure 19: Schemetic showing the relationship between the wake-generating bar and the test model.

Another method to control and manipulate laminar separation bubble is used by Choi and Kim (2010). Here, an optimization study of a pulsating jet was performed to manipulate the separation bubble behind the fence. The experiments were carried out in a circulating water channel and the vertical fence was submerged in the turbulent boundary layer as shown in

Figure 20. The parameters used for controlling the pulsating jet included the frequency, speed and velocity profile of jet, and the geometries including angle and location of nozzle.

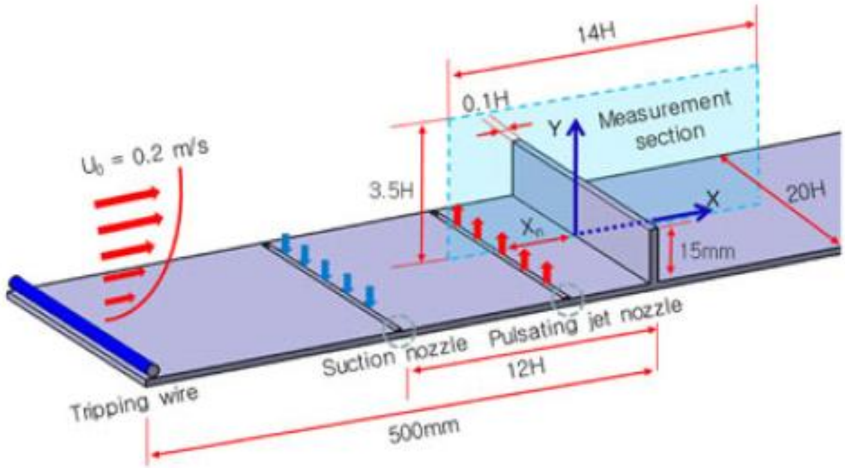
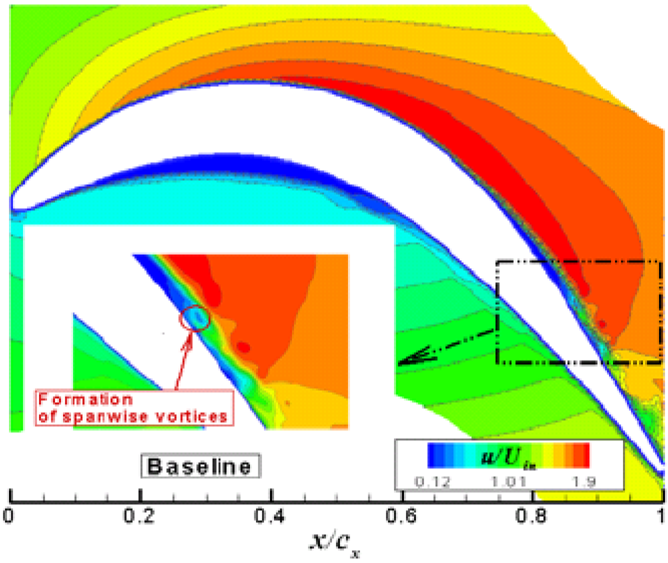


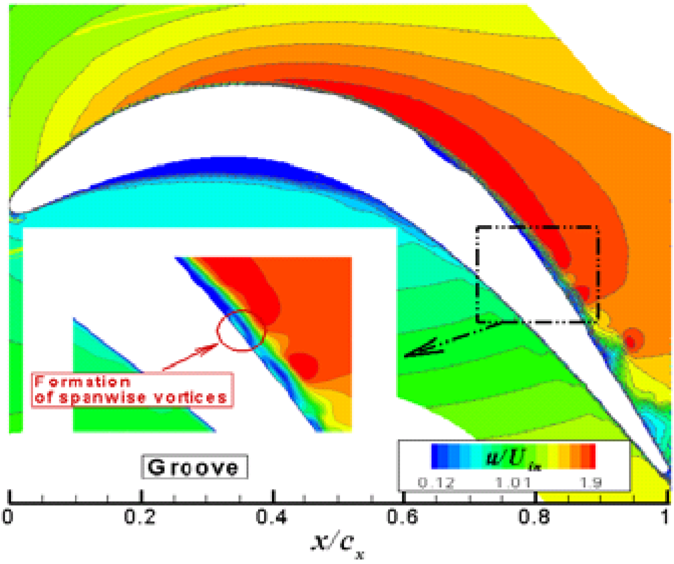
Figure 20: Schematic diagram of fence model with coordinate system.

The results of this experiment show that, there was a specific frequency, distance and angle that achieved the largest reduction of time-mean length of separation bubble. The maximum reduction appeared when Strouhal number was 0.05 and the pulsating nozzle distance was 1.75H with -30^{o} blowing angle of jet flow. The parametric studies of frequency and jet speed reveals there are universal optimal values. In addition, these values strongly depend on the upstream velocity condition and the change of jet profiles is less effective to reduce the separation bubble. It is showed that, the main cause of reduction was the vortex shedding phenomena from the separation bubble; this separation was governed by the vortex developed from the pulsating jet. If the vortex was weak and there was no separation from the bubble, the reduction of the bubble became smaller. The separation bubble can become even bigger than the uncontrolled fence flow under specific conditions.

Laminar separation bubbles generally exist on the suction surface of LPT (low pressure turbine) blade of gas turbines, with short bubbles slightly and long bubble notably impacting on the performance of blade (Mayle, 1991). So, one of the key to maintain the aerodynamic performance of high-lift LPT blade is to control the laminar separation bubble on the suction surface. As passive control techniques, the effectiveness of indented surface treatments such as dimples and v-grooves for laminar separation control on LPT blades were assessed by experiments (Lake et al., 1999). The dimples and v-grooves generally serve as vortex-generators that create streamwise vortex to enhance the mixing between high-energy freestream and low-energy boundary layer flow (Vincent and Maple, 2006). Recently, LES (Large-Eddy Simulation) computations were preformed (Luo et al., 2009) to investigate the mechanisms of a kind of spanwise groove for the passive control of laminar separation bubble on the suction surface of a low-speed highly loaded low-pressure turbine blade at Re = 50,000. They concluded, compared with the smooth suction surface, the numerical results indicate that: (1) the groove is effective to shorten and thin the separation bubble, which contributes the flow loss reduction on the groove surface, by thinning the boundary layer behind the groove and promoting earlier transition inception in the separation bubble; (2) upstream movement of the transition inception location on the grooved surface is suggested being the result of the lower frequency at which the highest amplification rate of instability waves occurs, and the larger initial amplitude of the disturbance at the most unstable frequency before transition; and (3) the viscous instability mode is promoted on the grooved surface, due to the thinning of the boundary layer behind the groove. The latter is justified from Figure 21. This figure shows the instantaneous velocity contour at mid-span for the baseline case and groove case, indicating the formation and shedding of the vortices. It is suggested that in the groove case viscous instability is accompanied by the inviscid K-H instability, and that the latter is responsible for the ultimate breakdown to turbulence



(a) Baseline



(b) Groove

Figure 21: Instantaneous velocity contour at mid-span.

To get a better understanding of the physical mechanisms which control the formation and structure of separation bubbles on rounded edges, an experimental studies has been performed in a visualization water tunnel (Figure 22) by Courtine and Spohn (2003). These experiments confirm the existence of a secondary instability which transforms the two-dimensional Kelvin-Helmholtz vortices into three-dimensional highly unsteady streamwise vortices. In addition the visualizations underline the strong influence of the bubble width on its breakdown length. The influence of the curvature (non-dimensional radius η) on the structure of the recirculation bubble is shown in Figure 23. The comparison of Figure 23a and 23b clearly shows that the separation angle increases with decreasing η.

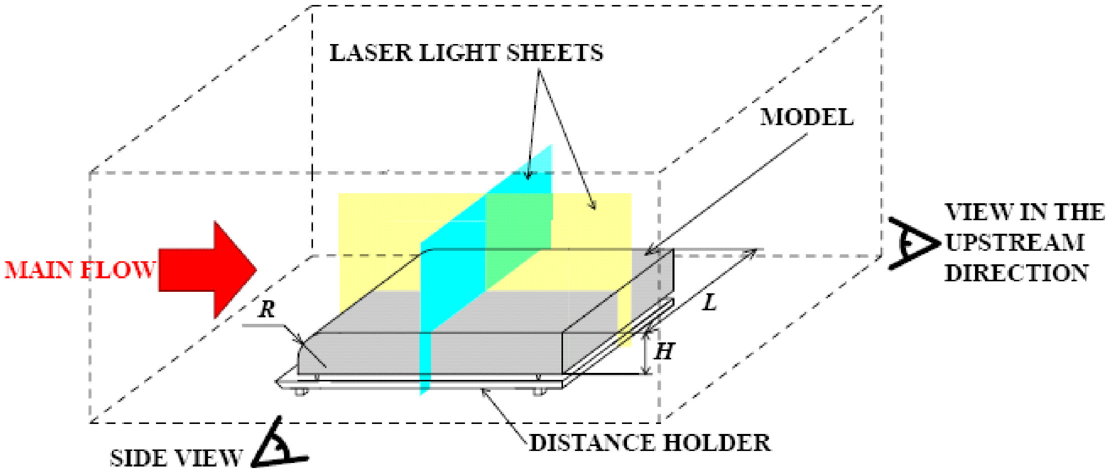
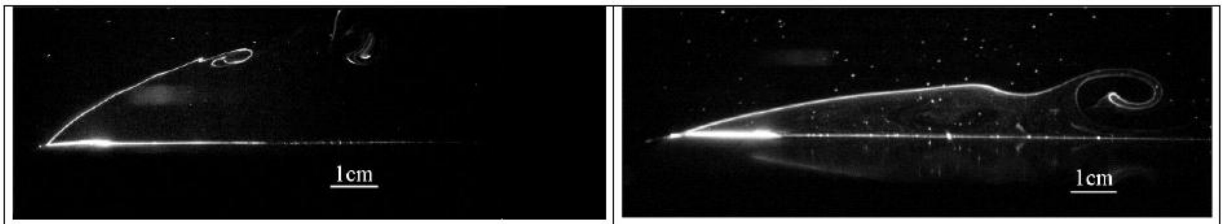


Figure 22: Experimental arrangement. The model is fixed outside the boundary layer of the working section, 2.5 cm above the tunnel wall.



(a) $\eta = 0.1$ (b) $\eta = 0.8$

Figure 23: Influence of the non-dimensional radius η (=R/H) of the rounded front edge on the structure of the separation zone at Re = 4000 and aspect ratio Λ = 8.8 (= L/H).

Earlier also, an active control of the leading-edge separation bubble of the blunt circular cylinder by a sinusoidal forcing in a Reynolds-number range 4,500-9,500 is investigated by Kiya et al., (1993). The forcing was applied to the separated shear layer in the form of an oscillating jet through a thin slit along the separation edge. Main results of this study may be summarized as follows.

(I) Three components of the time-mean and r.m.s, velocities q' were presented for unforced flows at a Reynolds number of 6,400. This result can serve as the database for the validation of turbulence models and direct numerical simulations.

(2) The unforced separation bubbles included a secondary separation bubble of the opposite circulation near the leading edge. The size of the secondary separation bubble decreased with increasing Reynolds number, disappearing at high Reynolds numbers of the order of 10^5 .

(3) The secondary separation bubble was not observed in the forced separation bubbles.

(4) The reattachment length decreased with decreasing forcing frequency in a range $f_{ex}d/U_\infty$ =2-9, thus attaining a minimum at a particular non-dimensional forcing frequency less than 2.

(5) The relation between the reattachment length and the forcing frequency appears to be only weakly dependent on Reynolds numbers in a range of 7,000-69,000.

The disappearance of the secondary separation bubble is brought about by the formation of larger and stronger vortices shortly after the separation edge by the forcing, as demonstrated by the flow-visualization photographs of Figure 24. This was also accompanied by the decrease of height of the forced separation bubbles.

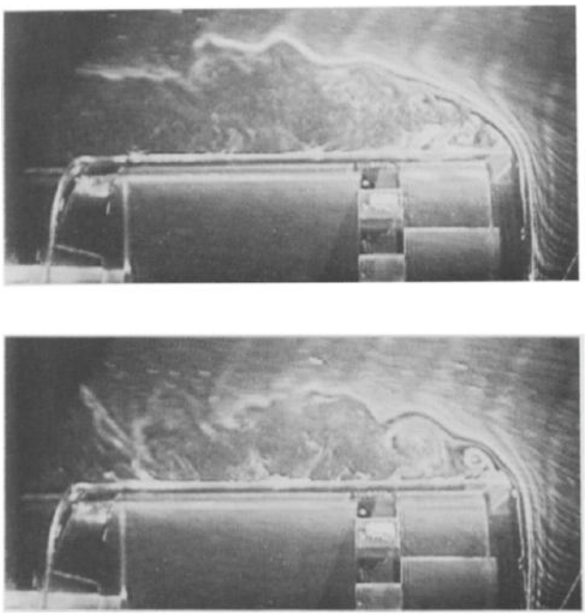


Figure 24: Visualized patterns of unforced flow and forced flow with $q'_f/U_\infty=0.07$ and $f_{ex}d/U_\infty=3.6$ at Re=7,000 (f_{ex} is excitation frequency and d is the diameter of cylinder). Flow from right to left.

Concluding remarks:

This paper showed a few research studies results carried out on different aspects of laminar separation bubble, majorly on basic concepts and characteristics, instability and control mechanism of LSB.

The complete understanding of the flow structure and transition mechanisms in the bubble region is still far from complete. While the influence of adverse pressure gradients on LSB has been studied extensively both numerically and experimentally, a better understanding of the physical mechanisms which control the formation and structure of separation bubbles is still to be uncovered.

Significant progress has been made so far on various aspects of the linear stability of a separation bubble, and most of the studies point to the inviscid instability associated with the separated shear layer to be the main mechanism. However, as shown by Diwan and Ramesh (2009), the primary instability mechanism in a separation bubble, in the form of two-dimensional waves, is inviscid inflectional in nature, and its origin can be traced back to the region upstream of separation.

In complex configurations BiGlobal linear analysis provides a unified means of addressing instability phenomena of separated flows as has been demonstrated by Theofilis et al. (2004).

The key of LSB control is to control laminar-turbulent transition since an earlier transition will move the re-attachment upstream. Gad-el-Hak (2000) has termed this “the easy task of flow control” (compared to turbulent separation control). Mainly because it suffices to provoke laminar-turbulent transition by some appropriate means without an urgent need for some highly sophisticated controller. In fact, a simple switch that turns LSB control on or off when appropriate could be sufficient, once the different flow situations are understood well enough. So the control methods of LSB discussed above was the main purpose of the present contribution to illustrate the underlying mechanisms in a rather brief manner.

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