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Experimental Investigation on Laminar Separation Bubble Over an Airfoil – A Review

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Abstract

Objectives: To provide comprehensive literature survey of laminar separation bubble over a low Reynolds number airfoil with reference to the conventional and non-conventional experimental technique using wind tunnel. **Methods/ Statistical Analysis:** For more convenient understanding, the various wind tunnel experimental techniques and advanced research progress in this field is presenting in table format. The table shows characteristics of laminar separation bubble over airfoil at different Reynolds number for various conditions. The table critiques the proof-based entire data about the Laminar Separation Bubble (LSB) traits (height and period), go with the flow traits differentiated, transition and reattachment locations and go with the flow visualization over airfoil were experimentally discovered at various angles of attack and Reynolds range, respectively. **Findings:** The current evidence supports the view that laminar separation bubble characteristics, behaviour and its effect over an airfoil. Most studies in this field have been done experimentally using Wind Tunnel with various techniques i.e., Surface Oil Flow Technique, Particle Image Velocimetry (PIV), Infrared Thermography (IT), Force Measurement and Hot-Wire Experiments, Smoke-Wire Experiment, Multi-line Molecular Tagging Velocimetry, Volumetric Three-Component Velocimetry (V3V), Time-resolved surface pressure sensor arrays, ESP (Electronically Scanned Pressure), Embedded Laser Doppler Velocimetry (ELDV), Fast Fourier Transform (FFT). **Application/ Improvements:** This paper describes the various techniques and characteristics of LSB which will be beneficial to design the low Reynolds number airfoil in order to minimize the drag and increases the aerodynamic efficiency for industrial applications.

Keywords: Flow Visualization Techniques, Low Reynolds Number, Laminar Separation Bubble Characteristics, Wind Tunnel Experiments

1. Introduction

The overall performance of all model flying machine is emphatically tormented by Laminar Separation Bubbles (LSB), which may additionally show up at low Reynolds numbers. This kind of separation bubble is because of a strong negative pressure gradient (pressure upward thrust along the surface), which impacts the laminar boundary layer to split from the curved airfoil surface. The boost of pressure is identified with the decrease of velocity towards the trailing fringe of the airfoil, which can be found in the velocity promulgation of the airfoil via Bernoulli's condition. The boundary layer leaves the surface through a tangential route, bringing about a wedge shaped separation location. The separated, yet on the equal time laminar glide is largely sensitive to unsettling influences, which is lengthy, the final purpose is to alternate to the turbulent region. The transition region (now not precisely a transition factor) is located at a distance from the airfoil at the outside boundary of the separated flow perimeter. The thickness of the now turbulent boundary layer develops rather quickly, shaping itself as a turbulent wedge, which may additionally achieve the airfoil surface once more. Another point of interest may the zone wherein the

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turbulent waft touches the surface once more is known as reattachment point. The volume encased by means of the districts of isolated laminar drift and turbulent waft is called a laminar separation bubble. Inside the bubble the waft is probably circling, the direction near the airfoil surface might also even be the alternative of the route of the outer drift. There's no energy change with the outside float, which affects the laminar separation to bubble very steady.

If the transition happens at a distance far from the airfoil surface, it would so happen that the turbulent flow wedge cannot reap the surface yet again. Therefore there is no reattachment and the bubble stays open. This sort of drift subject with a thick region of separated flow calls for an excessive drag and generally the lift disintegrates. Identical results are seen if angle of attack is extended past the greatest lift. Effective forces intend to evade the drag punishments and nonlinear behaviour of lift and moment coefficients, resulting from laminar separation bubbles, and are called tabulators. Airfoil with reflexes implies traces (as used on flying wing fashions) go through stronger from the low Reynolds number effects, because the reflex provides to the pressure gradient of their boundary layer. At high angles of attack or at low Reynolds numbers the flow may end up not able to surmount the destructive pressure gradient and fail to reattach. The flow pattern will then transmute right into a so-called lengthy bubble or right into a plenarily disunited flow (for airfoil flow: the main-edge stall). The difference between an extended and a short bubble is disputable and problematic to define for any kind of flow condition. In the case of airfoil flows, however, the formation of an extended bubble causes an ecumenical reorganization of the pressure distribution over the airfoil surface. The bubble effect on the pressure distribution is as a consequence different inside the two cases: Local and limited in the case of a short bubble, extra influential when it comes to a long bubble[1].

Figure 1 shows the laminar separation bubble, this laminar separation bubble may occur on aerodynamic bodies working at Re ≤ 10^6. The laminar separation bubble may occur in few conditions that are briefly depicted: The presence of the laminar separation flow of the laminar boundary layer because of an adverse pressure gradient; a turbulent flow change the separation layer inside; a turbulent reattachment. Under these conditions a separation area described by a moderate recycling flow and by a practically consistent pressure is framed. The presence of laminar separation bubble may raise two classes of issues: (i) The airfoil efficiency decreases, because of the airfoil drag increases; (ii) Due to the presence of extensive pressure fluctuations on account of laminar separation bubble bursting. This kind of complex phenomenon is a challenging task of aerodynamics and it has just been broadly considered by methods for a few creators with both experimental[2–11] and numerical techniques[12–17].

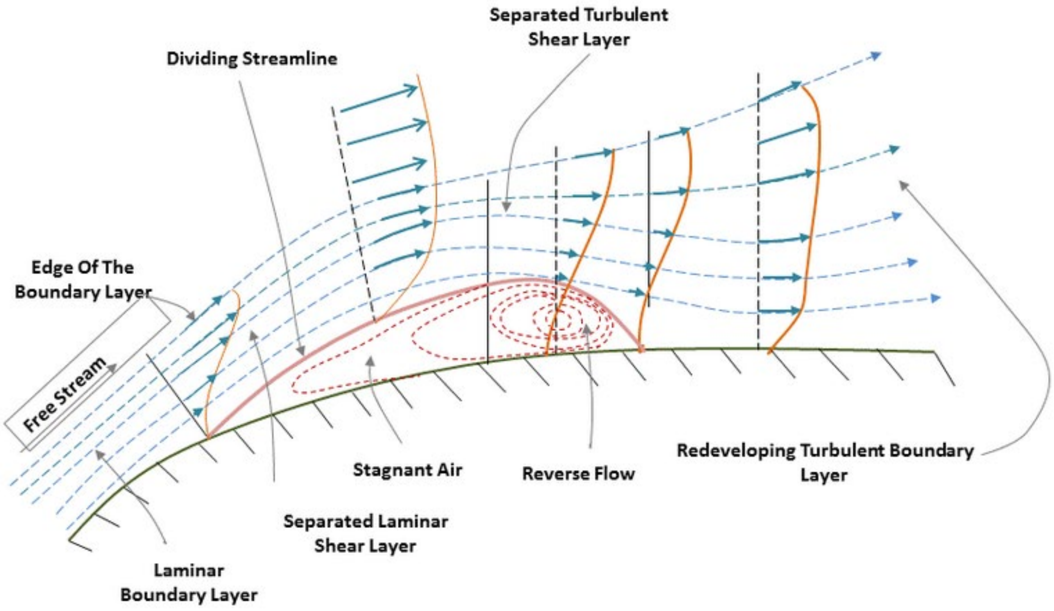

Figure 1. Nature of laminar separation bubble on a turbine blade[18].

1.1 Laminar Separation Bubbles: Early Studies

The presence of laminar separation bubbles became were first investigated[19] who in explored their influence at the stalling system of airfoils. In[20,21] further investigated the bubble behaviour near stall situations and, in view of this research, introduced a distinction between 3 styles of the stall, to be unique leading side, trailing side and thin airfoil stall[20]. Although, the most notable development within the comprehension of bubble structure and behaviour observed crafted by methods developed[22] who researched an expansive wide variety of bubbles created on a flat surface. The adverse strain gradient becomes made with the aid of setting an airfoil in upside-down position over the flat plate. This configuration enabled to carry out pressure and hot-wire estimations of many bubbles acknowledged for different Re and strain gradients. In[23] applied effects and further the advances in laminar[24] and turbulent[25] boundary layer concept for his particularly empirical bubble model. Many extra semi-empirical models had been proposed successively for a long time without usable results, but, introducing the most important development within the physical description of the bubble was with respect to version. Regardless of this effort, these semi-empirical attempts went unnoticed. They could not foresee the shape of the rise in all situations and its behaviour near stall. This flaw certainly suggests that the classical model of the bubble no longer seizes all the physics at play. In today's world, most study efforts target the unsteady characteristics of the bubble and at the influence of up-flow aggravations, incompletely changing the conventional attitude of the bubble.

2. Materials and Methods

A search was made on the Google Scholar database on 3rd July, using specific key words (Laminar Separation Bubble over airfoil and experimental investigation on LSB over Airfoil). The key word "Laminar Separation Bubble and Experimental Investigation on LSB over airfoil" generated about more than 1000 results. The results generated included all other publications that had the words "Laminar Separation Bubble" or "Experimental Investigation on LSB over airfoil" in them. Searches were also made on other databases such as Scopus Indexed Journals. Other key words, such as 'Wind Tunnel Experiment' or 'Flow Visualization over an airfoil', were also used. The search and re-search in all database yielded near-similar results. Selection criteria for inclusion were made to eliminate all non-related or irrelevant publications. The main criteria for inclusion in phase one was that the publications had to be an original research paper and International Conferences specifically written on English, with at least one of the specific sub-criteria, as below:

(a) Laminar Separation Bubble (LSB) traits (height and duration) and flow characteristics at separation, transition, and reattachment region over low Reynolds range airfoil.
(b) Measurement of LSB over low Reynolds number airfoil.
(c) Experimental Technique: Surface Oil Flow Technique, Particle Image Velocimetry (PIV), Infrared Thermograph (IT).

Low Speed Wind Tunnel: Force Measurement and Hot-wire Experiments, Smoke-Wire Experiment, Multi-line Molecular Tagging Velocimetry, Oil Film Interferometer, Volumetric Three-Component Velocimetry (V3V), ESP (Electronically Scanned Pressure) Scanners, Embedded Laser Doppler Velocimetry (ELDV) and stereo-PIV, Fast Fourier Transform (FFT) etc.

All publications fulfilling the stated criteria were then selected for the next phase of the review process. Elimination of search results was due to them not fulfilling at least one of the 3 sub-criteria. Criteria for inclusion in phase 2: All articles selected in phase one were put into specific areas of classification, which were based on the foundational area of studies for Laminar Separation Bubble. The areas of classifications discussed in this paper are: (a) LSB Measurements; (b) LSB behavior; (c) LSB characteristics; (d) LSB - Experimental Technique and (e) Other areas outside LSB (including Numerical Investigation) summarized in Table 1. Publications that fell in the 'Other areas i.e. numerical investigations of LSB' will be presented next part of this review.

3. Results and Discussion

3.1 Relevant Studies

The background knowledge was taken from a review of chapters in relevant textbooks in the field of Aerodynamics. For the foreground knowledge, a total of

98 articles were found from the online database (Google Scholar); 84 articles were excluded because their titles, abstracts, or contents were not related to the aims of this article (Figure 2). Finally, 14 articles were considered as relevant studies (Table 1). Table 1 shows a critical review of the studies that fulfilled all the criteria mentioned above are presented as follows.

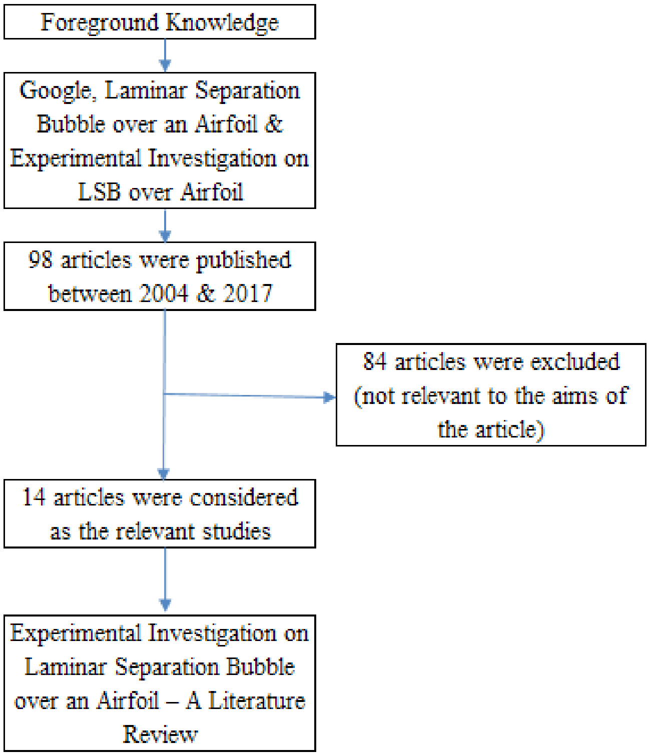

Figure 2. Process of the review.

3.2 Research Gap

In[26] this case, the relation of the lift with vortex circulation along with position and size of vortices was not investigated. In[27] Re = 50000 and 75000: The lift and drag coefficient increases as the AOA increases. But Re = 25000 there is an unprecedented steep rise for the drag coefficient and also stall can be found in this range of Re number. In[28] introducing surface roughness can effectively eliminate the observed anomalies in the lift curve lope, which further confirms that separation bubbles are responsible. In[29] finding the accurate LSB characteristics over airfoil is more difficult. The results are challenging between computations and experiments between different experiments. Moreover it's a complex task to validate computational results and experimental results within this region.

In[30] the airfoil completed poorly for Re = 40000 and 60000 for a number of angles of attack due to laminar boundary layer separation. Quick bubble transition is dominated by way of Kelvin-Helmholtz instability. Long bubble's transition manner is currently unclear, but it is suspected that viscous outcomes play an extra vital function than in short bubbles. Oil Film Interferometry (OFI) couldn't be performed on all the low perspective and some of the medium perspective test instances. In[31] the rate of increase in the laminar separation bubble through span wise and wall-normal Re normal stresses within the region suggest the evolution of 3D disturbances. In[32] the Low Reynolds airfoil is associated with air packets of growing disturbances propagating via the shear layer.In[33] increasing the AOA, the laminar separation bubble bursting takes vicinity, the flow become turbulent and detaches suddenly i.e., "Abrupt Stall".

In[34] regrettably no experimental work with blowing/suction for NACA 2415 airfoil. In[35] NACA 0012 airfoil is not that suitable for such a research because of drastic modifications inside the bubble length and its location. In[36] if the AOA became higher i.e., >12^0, the separation bubble found to burst to cause airfoil stall, the coefficient of lift reduced and the drag coefficient increased significantly. In[2] in a few conditions, the cyclical bubble formation and detachment may additionally induce strain pulses and consequent vibration phenomena. [The laminar bubble behaviour seems to be lesser dependent on the Reynolds number apart from the lower tested Re of 60k]. In[37] the finely established vortices found at excessive incidences and their complicated evolution for the duration of a few phases of the pitching isn't always but sufficiently predicted by means of two-dimensional computations. In[38] Flow velocity near the leading edge fluctuated in synchronization with this flow oscillation [flow over the airfoil is oscillating at a low frequency near stall].

4. Conclusion

Understanding of Laminar Separation Bubble (LSB) and its flow characteristics is essential to design the low Reynolds number airfoil for wide range of engineering applications to amend the aerodynamic characteristics and Flow characteristics. Predicated on the systematic review performed, it can be concluded that there was not

Table 1. Summary of experimental investigations

Author, Publication Year, [refs]	Airfoil (Characteristics) & Reynolds Number	Experimental Technique and Characteristics investigated	Outcomes/Conclusions
In[26]	SD7037 C = 26 mm, AOA = 9° to 14°, Stall angle of attack 11°, Re: 3.8×10^4	Wind tunnel, PIV, Infrared Thermography Methods (IT) LSB characteristics (height and length) & flow characteristics at transition and reattachment points.	The height of the LSB 1 to 2 mm which is about 5% to 6% of chord length (AOA 12° and 13°) Conclusion: Behaviour of the low Reynolds number flow over a SD7037 airfoil both steady and unsteady conditions by using PIV, IT & DIT.
In[27]	NACA 4412, C = 10 cm, Span = 10 cm. Re: 25000, 50000 and 75000	Low speed wind tunnel: Force Measurement and Hot-Wire experiments, Smoke-Wire experiment. Flow separation and vortex shedding	Low speed wind tunnel: Re = 25000, Stall angle = 12°, $C_{L,max}$ = 0.9 Re = 50000, Stall angle = 16°, $C_{L,max}$ = 1.25 Re = 75000, Stall angle = 18°, $C_{L,max}$ = 1.35 smoke-wire experiment: Re 25000: The laminar separation bubble moved towards LE over the airfoil when the AOA changed from 8^0 to 12^0 Re 50000: The flow separation occurs at 16^0 AOA but even though the laminar separation bubble is found at 12^0. Re 75000: The perspective of the laminar flow separation occurs at 19^0 and the main-part separation is likewise seen at a 19^0. Hot wire anemometry machine: Re 25000: The velocity at the wake region reduced from 1.034 to 0.6 at 16^0 AOA. The rate further decreased from 1.074 to 0.37 at 20^0. The same decreasing is discovered at Re variety of 50000 and 75000. Conclusion: It ends up noticeably presumed that as Re range broadened, the slowdown edge extended. What's more, the partition bubble moved towards LE over the airfoil as the approach expanded.
In[28]	NACA 0021 and NACA 65-021 Two airfoil selected: NACA of 21% thickness-to-chord ratio Re: 120000	Wind tunnel, 6-component load cell. Laminar separation bubbles	Force Measurements: NACA 0021 & NACA 65-021: increasing lift curve slope for $5 < \alpha < 8^0$. NACA 65-021: Separation Bubble occurs between $0 \le \alpha \le 4^0$. Conclusion: At high angles of attack, whilst the suction-facet laminar separation bubble has moved near the leading facet, the plain camber of a NACA 0021 airfoil is multiplied, as a consequence allowing the airfoil to generate extra carry that could be predicted from the geometrical seasoned file shape. At the point in which the separation bubble "bursts", there's an unexpected loss in elevate. The terrible carry phenomenon observed for the NACA 65-021 airfoil is associated with a pressure-aspect separation bubble which alters the powerful camber in this surface.

In[29]	SD7003, AOA and Chord varies. Re: 2 X 10^4 to 4 X 10^4	Water tunnel. Multi-line Molecular Tagging Velocimetry. Laminar separation and reattachment locations	In this article, the laminar separation and reattachment locations are suggested for the constant flow with the flow over an SD7003 airfoil at distinct angles of attack and Rec wide variety in the variety 2 x 10^4 - 4 x 10^4. Conclusion: The trial portrayal of the laminar separation rise over low Reynolds amount airfoil is additional troublesome than typically analysed. This confuses the approval of computational records towards probes this elegance of flows.
In[30]	BE12037M10 The model was constructed in two aluminum halves, encasing stainless steel tubings for 40 pressure ports. Span = 0.736m C = 0.254m, AR = 2.9 Re = 100,000, 150,000, and 200,000	Wind tunnel, Dantec conventional hot wire probe, with a 5μm copper-plated tungsten wire with a sensing length of 1mm, Oil film interferometry (Xiameter PMX-200 20CS silicone fluid was used for the experiment) 1. The separation, transition, and reattachment location through pressure distribution. 2. The boundary layer tripping effectiveness.	The laminar separation bubbles formation at suction aspects of the airfoil at Reynolds numbers of 40000 and 60000 has been investigated. The reaction of laminar separation bubble to the intrusion of a conventional hot-wire probe changed into systematically investigated for Reynolds numbers of 100000, 150000, and 200000 for a number of angles of attack between 0^0 to 9^0. Oil film interferometry became used to degree the time-averaged shear stress distribution. Conclusion: 1. The improvement in lift-to-drag ratio was substantial for Rec = 40,000, where the half round and rectangular trips increased it to 32.1 and 39.0 respectively, both occurring at 8^0. 2. It is concluded that the disturbances introduced into this highly unstable region caused the localized effects seen. 3. The viscosity of the oil used limited the test space to only include flow conditions with relatively high shear stress. As a result, OFI could not be performed on all of the low angle and some of the medium angle test cases
In[31]	NACA4412, C = 0.3048m Span = 0.610m, Different AOA Re: 50000	Wind tunnel, Volumetric Three-component Velocimetry (V3V), Measurement of LSB	Span-wise Reynolds number regular stresses and Reynolds number shear stresses develop in the transition and reattachment regions. Conclusion: The reverse flow action faster in the turbulent portion so that the bubble accomplishing velocities of more prominent than 10% of the free development pace with a returned-flow coefficient of 70%.
In[32]	NACA 0018, C = 200 mm Span = 600 mm, Re: 100000	Wind Tunnel: time-resolved surface strain sensor arrays, sixty-five strain taps of 0.4mm diameter are allotted alongside the airfoil chord on the centre span plane. Flow visualization, pace field mapping, surface stress fluctuation measurements, and balance analysis	NACA 0018, Rec = 100000 and AOA = 0^0, 5^0, 10^0, and a 15^0. Investigated velocity field mapping, time-resolved surface stress measurements, and stability analysis. Conclusion: Hot-wire measurements: separation bubble actions upstream, decreases in length, and exhibits better disturbance growth fees because the angle of assault is increased. However, the separation bubble top does no longer change monotonically with the angle of attack. Comparison of the improvement of electricity spectra and RMS: surface stress sensor arrays can be used to decide whether shear layer reattachment happens, the region of the separation bubble, and the frequency band of developing disturbances.

			Velocity profiles; Several separated shear layer experiments discovered an exponential decay with displacement thickness Reynolds range of the share distinction between the most growth rates predicted from viscous and inviscid spatial linear balance analyses.
In[33]	NACA 0015, C = 0.31m AOA= -5^0 to 25^0, Re: 0.2E06 to 0.6E06	Wind tunnel, Surface Oil flow Technique (Oleic Acid and Transformer oil, Proper proportion of Titanium Oxide), ESP (Electronically Scanned Pressure) Scanners. Laminar separation bubble	For various Re and AOA, the boundary layer and separation bubble characteristics are predicted and analysed. Conclusion: If the AOA increases, the laminar separation bubble bursting takes vicinity, the flow become turbulent and detaches suddenly i.e. "Abrupt Stall".
In[34]	NACA 2415, AOA = 8^0, Re: $2x10^5$	Wind tunnel, Oil flow visualization. Laminar separation bubble characteristics	Predicted the LSB characteristics over a NACA 2415 airfoil about 30% of chord. Conclusion: With the help of oil flow visualization technique identified a LSB over NACA 2415 around 30% chord.
In[35]	NACA 0012 and LA2573a, C = 0.3048 m, AOA 0, 2, 4 and 6 degrees, Re: 250,000 and 650,000	Wind tunnel, Sensor. Behaviour of the laminar separation bubbles	The behaviour of the laminar separation bubbles as functions of AOA and Reynolds numbers for the NACA 0012 and LA2573a airfoil. Conclusion: NACA 0012 airfoil is not that suitable for such a research because of drastic modifications inside the bubble length and its location. LA2573a airfoil certain level it's suitable for such a research because of small adjustments inside the bubble location and length of the bubble.
In[36]	NASA low-speed GA (W)-1, C = 101 mm Maximum thickness = 17% chord length, Re: 70,000	High-resolution particle image velocimetry (PIV). Transient behaviour of laminar flow separation	Measured surface pressure distribution across the airfoil: Predicted transient behaviour of laminar flow separation i.e. separation, burst, stall etc. at 12^0 AOA. PIV Measurement effects: The critic factors i.e., separation, transition, and reattachment locations of the separation bubble identified from the PIV measurements. Lift and drag coefficients of the airfoil: As the AOA increases 12^0 the laminar separation bubble become observed to burst, so that the stall, the lift coefficient decreases and drag coefficient increases. Conclusion: The separation, transition, and reattachment locations are identified with the help of PIV measurements.
In[2]	RR3823HL, AOA = 5^0& 12^0, Max thickness = 8.35 %, Max camber = 3.38 %, Re: 60k, 100k, 150k, 200k	Subsonic wind tunnel, IR Technique. Laminar separation location, The transition location, Turbulent reattachment location.	With the help of IR thermographic technique identified the laminar bubble phenomenon. Conclusion: Laminar separation location, The transition location, Turbulent reattachment location depends on AOA and Reynolds number, to understand the bubble behaviour.

In[37]	OA209, C = 0.2m, AOA ± 6°. Re: $0.7x10^5$	Wind tunnel, Embedded Laser Doppler Velocimetry (ELDV) and stereo-PIV. Boundary layer profile and the traits of the flow velocity distribution	The dynamic stall condition has been investigated in a low-speed wind tunnel. Conclusion: The results validated against ELDV records and CFD results, the separation bubble have been observed and also the velocity magnitudes are acceptable agreements.
In[38]	NACA 0012, AOA = 11.5^0, Span = 0.2 m, C = 0.2 m. Re: 1.3×10^5	Low speed suck-down type wind tunnel, particle image velocimetry, Fast Fourier Transform (FFT), smoke flow visualization (Oil mist: Ondina oil). Quasi-periodic characteristics near the onset of airfoil stall	Investigated LSB behaviour and its characteristics over NACA 0012 Conclusion: The results indicated flow fluctuations of about 1.5 Hz - 3 Hz near the onset of stall ($\alpha = 11.3° - 12°$). The amplitude of the fluctuation is the greatest and the fluctuation occurred quasi-periodically at $\alpha = 11.5°$. Formation of a large vortex near the leading edge (at about x/c = 0.05) was observed, this vortex may be strongly related to the mechanism that generates the flow oscillation.

enough research found on the Laminar Separation Bubble (LSB) characteristics (height and length). Each author describes the Laminar Separation Bubble (LSB) characteristics for sundry Reynolds number, at what Reynolds number the genuine laminar separation bubble occurs and its authentic behaviour corresponding Reynolds number is still inhibited.

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