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ON THE FORMATION OF A LAMINAR SEPARATION BUBBLE

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Abstract. The formation of a laminar separation bubble on a flat plate (LSB) was experimentally studied from the beginning of the laminar separation until the bubble reached its quasi-stationary regime. The experiments were carried out in a low-turbulence, closed-return water channel. The pressure gradient was imposed by a false wall, which created a convergent-divergent channel. The bubble was formed in the divergent part corresponding to the adverse pressure gradient region. A vibration ribbon located upstream of the LSB introduced controlled disturbances into the boundary layer. Velocity fields were measured using the two-dimensional time-resolved particle image velocimetry technique (TR-PIV). Phase-locked and ensemble average schemes were used in data acquisition and post-processing respectively. The results show the bubble formation process in great detail, allowing us to characterize the main topological characteristics and some integral parameters. These results are original in the literature and can contribute to describe the bubble formation and its dynamics.

Keywords: Asymptotic Growth of a Laminar Separation Bubble, Time-Resolved Particle Image Velocimetry, Separated boundary layer

1. INTRODUCTION

Airfoils operating at low Reynolds numbers (5×10^5 to 10^6), can exhibit laminar boundary layer separation when subjected to a strong adverse pressure gradient, Ducoin *et al.* (2016), Acikel and Genc (2018). In these conditions, the separated boundary layer is highly unstable and may undergo a laminar-turbulent transition and subsequent reattachment due to the increase in momentum transfer from the external flow to the region near the wall. The recirculation region formed between the separation and the reattachment point is known as laminar separation bubble (LSB), Gaster (1967). The presence of LSBs is typically related to higher fuel consumption, CO_2 emission, aeroacoustic noise, mechanical vibrations, and consequently loss of efficiency. The growing interest in technological applications such as drones, unmanned aerial vehicles, hydrokinetic turbines, ultrahigh-lift blades, and low-pressure turbine blades motivates continuous efforts to improve low Reynolds number aerodynamic performance. This work focuses specifically on the scenario of variable environmental disturbance conditions, such as in low-pressure turbine blades (LPT), where the wake of a previous stage influences the flow conditions in a subsequent stage. This interaction can periodically induce suppression and further regeneration of the bubble. The first systematic studies on LSBs provide a general description of the quasi-steady bubble under statistically non-varying environmental conditions Horton (1967), Gaster (1967). Later, studies focused on the transition mechanisms of the separated boundary layer. It was recognized that linear stability theory can reasonably predict the growth of small fluctuations in the separated shear layer near the separation location. In this region, the dominant mechanism is the inflectional Kelvin-Helmholtz instability. This scenario seems valid for relatively low intensity of the reverse flow. A comprehensive review of the stability characteristics of LSBs can be found in Marxen and Rist (2010)'s work. Few recent studies have focused on the transient dynamics of the LSB, aiming to describe the bursting phenomenon. The bubble bursting corresponds to the scenario in which the bubble varies from a small bubble to a large one. In the work Toppings and Yarusevych (2023), the bubble bursting was evaluated by changing the Reynolds number in an aerodynamic profile. In that case, the base flow was modified by a change in environmental conditions. On the other hand, Michelis *et al.* (2017) investigated the transient response of a bubble subjected to tonal and broadband disturbances. The bubbles have a transient behavior in both works, but their formation process from an incipient separation to a quasi-steady regime was not studied. This work aims to help fill this gap.

2. METHODOLOGY

The experiments were carried out in a closed return open water channel of the fluid engineering laboratory at the Pontifical Catholic University of Rio de Janeiro. This water channel has a low turbulent intensity, less than 0.5 % at the inlet of the test section, the test section has $4 \times 0.86 \times 0.64$ m in length, width and height. The two-dimensional time-resolved particle image velocimetry technique was used to assess the velocity fields. A Litron LDY-300 laser system was used as a light source. Due to the large length of the bubble in its quasi-stationary condition, it was necessary to use two Phantom Miro M340 cameras to capture the entire field. The acquisition frequency was 50 Hz. The formation of a laminar separation bubble was induced by a strong adverse pressure gradient produced by a false wall that, together with a flat plate, forms a region of convergent-divergent section. The bubble was formed in the divergent region. To introduce controlled disturbances, a vibrating ribbon (VR) was mounted upstream of the bubble formation region and inside the boundary layer. The VR oscillation frequency was set to 2.5 Hz, corresponding to the frequency of the most unstable disturbance found in preliminary experiments. The oscillation of the VR is initially set to high amplitude. This triggers boundary layer turbulence and inhibits bubble formation. After a few seconds of turbulent flow, the disturbance excitation is rapidly changed to low-amplitude perturbations. Under this condition, the boundary layer relaminarizes, and there is a rebirth of the laminar separation bubble. The LSB expands until it reaches a quasi-steady regime. The velocity fields of this process were captured with PIV over 20 phase-locked ensembles, allowing for ensemble averaging. Figure 1 shows a general sketch of the test section.
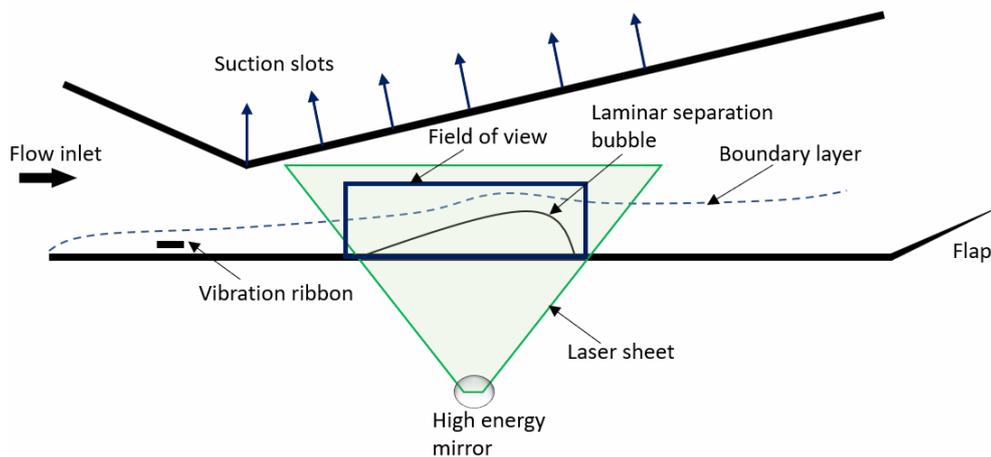

Figure 1. Simplified scheme of the test section.

3. RESULTS

Before each experimental campaign, the separation bubble was qualitatively examined using the dye flow visualization technique. Figure 2 shows a snapshot of the laminar separation bubble in its quasi-steady state. In the front part of the bubble, the separation of the boundary layer is clearly visible. Below the region of maximum bubble height, one can observe lines of dye bent toward the inlet, indicating a region of reverse flow. Above the maximum height region, the particles follow the mean flow path. Thus, there is strong shear that promotes vortex formation. These vortex grows and gains strength before being ejected. The maximum intensity of the reverse flow is usually observed right below the core of such vortex. On the right-hand side of the figure, one can observe a previously ejected vortex downstream of the maximum height of the LSB. The ejected vortices continue downstream, lose coherence, and dissipate further in the turbulent flow. This general picture represents a typical quasi-stationary LSB.

Some integral parameters such as displacement thickness, momentum thickness, and shape factor were evaluated during the bubble formation process. The figure 3 shows the temporal evolution of displacement thickness during the asymptotic growth of the LSB. This parameter shows an almost monotonic variation toward its quasi-stationary state depicted by a thick black line. Note that the zero coordinate corresponds to the location of the non-dimensional separation point. Thereby, small bubble movements upstream are compensated to show the distribution with respect to the separation point. The same coordinates are used for the next two figures.
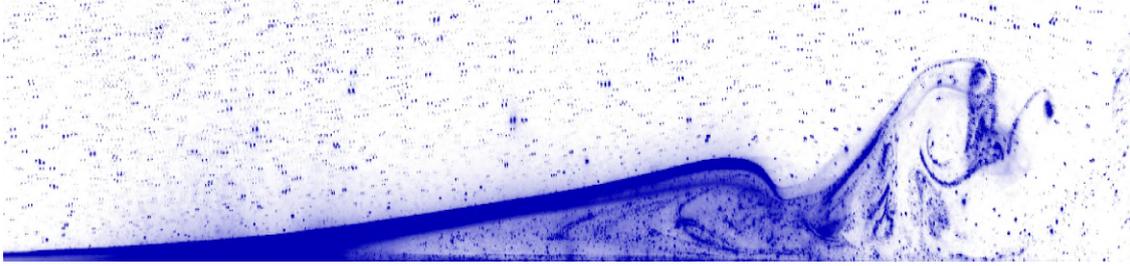
Figure 2. Flow visualization of a snapshot of a laminar separation bubble during its quasi-steady regime. The flow goes from left to right. The blue color was artificially introduced according to the intensity of the pixels to highlight the bubble structure.
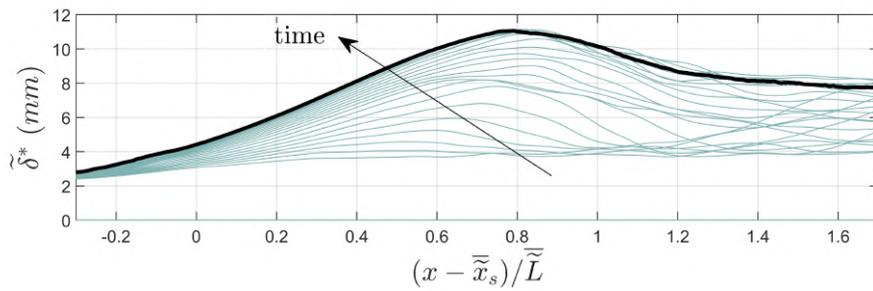

Figure 3. Solid green lines: evolution of displacement thickness during the asymptotic growth of the bubble. Solid black line: mean displacement thickness in the quasi-stationary regime. x: streamwise coordinate. $\widetilde{\overline{\overline{x}}}_s$: instantaneous separation point. $\overline{\overline{\widetilde{L}}}$: bubble length.
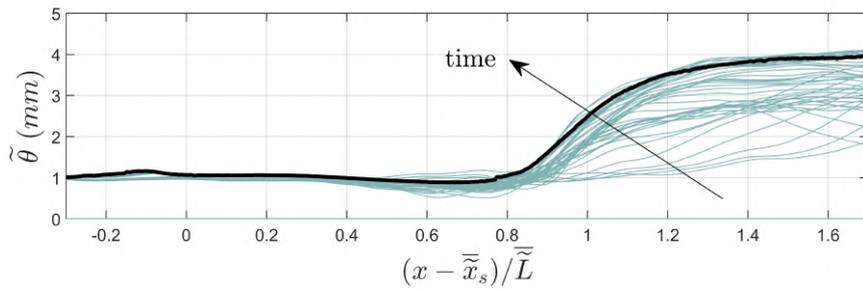

Figure 4. Solid green lines: evolution of momentum thickness during the asymptotic growth of the bubble. Solid black line: momentum thickness in the quasi-stationary regime. $\widetilde{\overline{\overline{x}}}_s$: instantaneous separation point position. $\overline{\overline{\widetilde{L}}}$: bubble length.
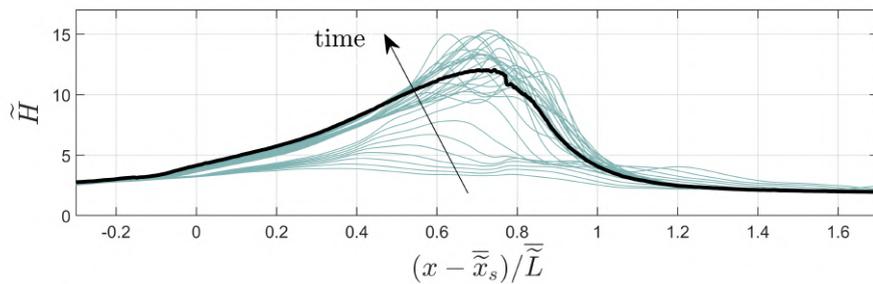

Figure 5. Solid green lines: evolution of shape factor during the asymptotic growth of the bubble. solid black line: shape factor in quasi-stationary regime. $\widetilde{\overline{\overline{x}}}_s$: instantaneous separation point position. $\overline{\overline{\widetilde{L}}}$: bubble length

The temporal evolution of the momentum thickness is shown in Figure 4. According to this figure, the momentum thickness around the separation location ($(x - \overline{\tilde{x}}_s)/\overline{\tilde{L}} = 0$, does not change significantly during bubble formation. This suggests that momentum thickness can be, indeed, a relevant parameter for separation prediction regardless of the bubble state or the boundary layer disturbance level. Moreover, it is a highly suitable parameter for a length scale in non-dimensional variables.

The temporal evolution of the shape factor is shown in Figure 5. The figure shows shape-factor oscillations in the region of maximum height of the bubble, which can be attributed to oscillations in momentum thickness in the same region. Outside this region, the behavior of shape factor display an almost monotonic variation in time. The shape factor drops rapidly downstream of the maximum height, indicating a rapid laminar-turbulent transition near the reattachment point.

The evolution of the dividing streamline during the asymptotic growth of the laminar separation bubble is shown in Figure 6. The separation point converges smoothly towards its quasi-stationary position, while the reattachment point oscillates significantly around its mean quasi-stationary position. This is because the dividing streamline breaks when vortices are ejected from the rear part of the bubble, causing the oscillation of the instantaneous reattachment point. For the same reason, oscillations are also observed in the position of the maximum height.
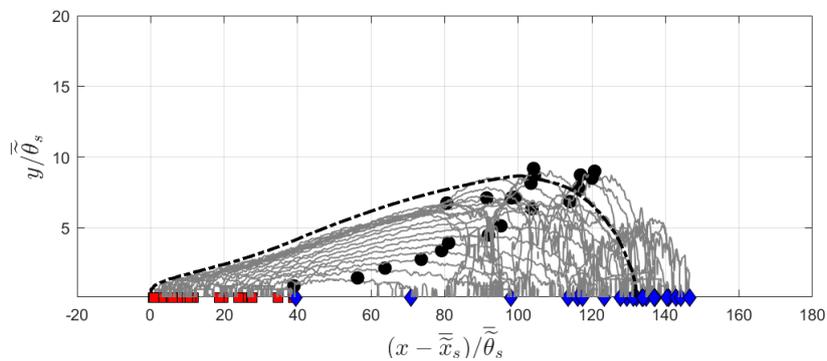

Figure 6. Evolution of the instantaneous dividing streamlines during the bubble formation. markers: (red square) position of the instantaneous separation point. (black circle) position of the instantaneous maximum height. (blue diamond) position of the instantaneous reattachment point.
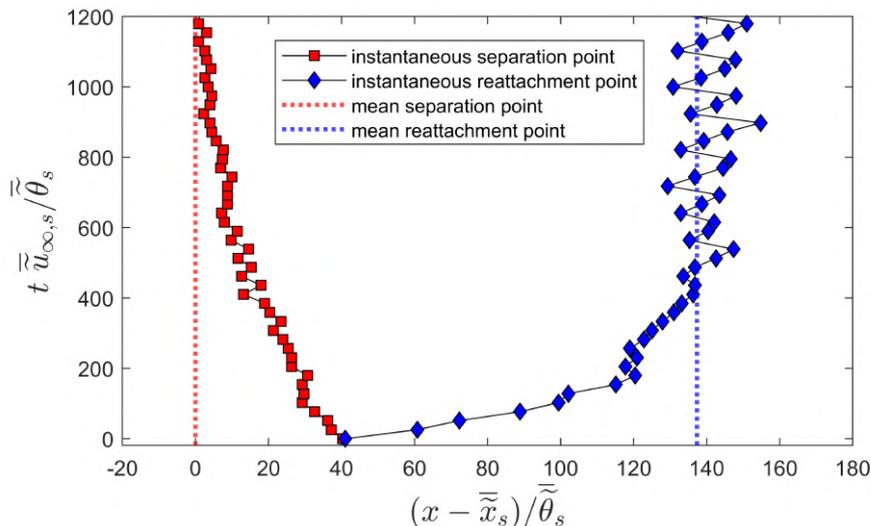

Figure 7. Temporal evolution of the streamwise position of the separation and reattachment points.

The asymptotic growth of the laminar separation bubble can be observed from another perspective, as depicted in Figure 7. This figure shows the temporal evolution of the streamwise position of the separation and reattachment point. Note that the reattachment point smoothly approaches its quasi-stationary state, with a change in the expansion rate at approximately the dimensionless time 600, this change coincides with the moment when the vortex ejection becomes more coherent and more intense. On the other hand, notice that the reattachment point expands more explosively until time 450. Then, the vortex ejection starts and the reattachment point begins to oscillate in a limited cycle. Initially, the

ejected vortices are weaker, becoming more intense and coherent. An interesting observation is that at time approximately 180 the expansion rate of the reattachment point undergoes a change, and the expansion becomes slower. This suggests a change in the mechanism of flow reattachment. Within the period between 180 to 450, the intensity of the reverse flow reaches values up to 35%, suggesting that there could be mechanisms of absolute and/or global instability during the asymptotic growth of the bubble. However, this hypothesis needs to be examined in more detail. In future work, an instability analysis of the asymptotic growth process of the bubble will be performed.

The velocity fields of the laminar separation bubble formation are shown in figure 8. The high spatio-temporal resolution of the data allows us to examine the bubble-formation process in detail. The left column of the figure shows the evolution of the stream-wise velocity component. Note how the boundary layer grows and expands, the intensity of the reverse flow gradually increases until the recirculation region breaks and ejects the first vortex, from then on, the vortex shedding continues periodically. The right column of the figure shows the evolution of the wall-normal velocity component; note how the vortices gain strength, coherence, and periodicity. It is important to remember that the periodicity and coherence found in these results are due to controlled environmental perturbations, both in frequency and amplitude. The dimensionless time indicated in the white boxes in Figure 8 is the dimensionless time indicated on the vertical axis of Figure 7.
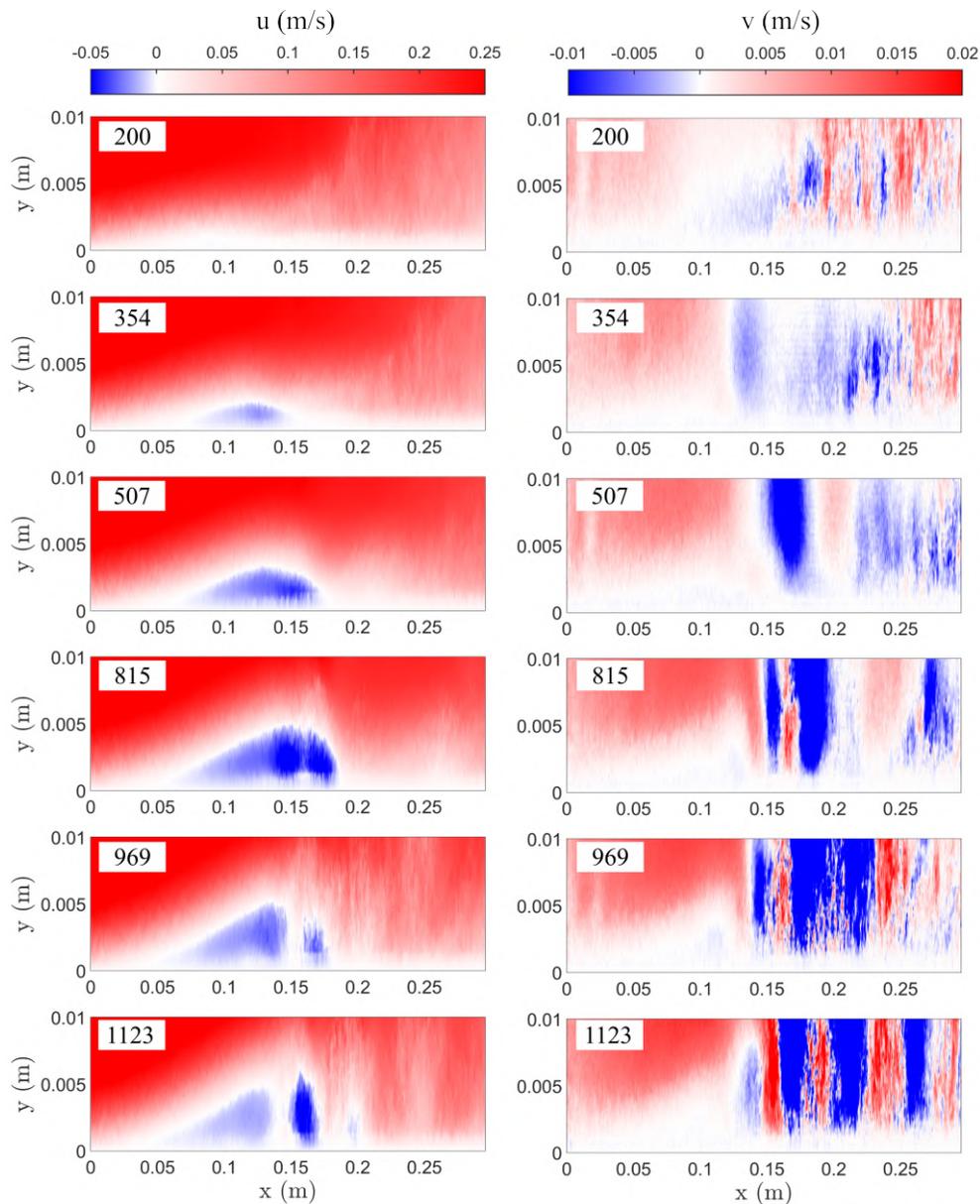

Figure 8. Streamwise velocity component and wall-normal velocity component of the asymptotic growth of the laminar separation bubble under forcing conditions. The dimensionless time of each velocity field is indicated in the white box. For reference see figure 7

4. CONCLUSIONS

In this work, the formation process of a laminar separation bubble under forcing conditions was studied from an incipient separation of the boundary layer until the bubble reaches its quasi-stationary regime. The growth and expansion of the LSB were evaluated through the assessment of the separation point, the reattachment point, and the velocity fields; when the bubble is subjected to controlled environmental conditions, the ejection of vortices exhibits coherence and periodicity. During the bubble growth process reverse flow intensity peaks in the order of 35% were found, which suggests the possibility that absolute and/or global instability mechanisms are dominant during bubble formation. Due to the sensitivity of the bubble to external perturbations, setup an adequate test section is a great challenge. These experimental results are unprecedented in the literature and help characterize and explore the physical mechanisms involved in bubble formation.

5. REFERENCES

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6. RESPONSIBILITY NOTICE

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