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EXPERIMENTAL STUDY OF THE TRANSIENT RESPONSE OF A LAMINAR SEPARATION BUBBLES

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Abstract. *This work investigates the transient response of a laminar separation bubble (LSB) subjected to controlled periodic disturbances under different adverse pressure gradients, the periodic wake-LSB interaction is usually found in cascades of turbine blades that operate at low Reynolds numbers, which are present in aircraft engines and gas turbines. The wake-LSB interaction is associated with the generation of aero acoustic noise, mechanical vibrations, increased drag and consequently performance loss. Given the complexity of the involved phenomena many features of wake-LSB interaction are not yet well understood. In addition, such a problem is difficult to be reproduced accurately by using turbulence models in numerical simulations. To shed some light onto the description of the wake-LSB interaction, a series of experiments were performed in a low turbulence intensity water channel. The laminar separation bubble was formed on a flat plate and an adverse pressure gradient was induced by a false wall. This wall created a convergent-divergent channel, and the bubble was formed on the region of adverse pressure gradient. Tollmien-Schlichting waves were excited in the boundary layer with a vibrating ribbon. The disturbance source was located upstream of the LSB formation region. Velocity fields were acquired using the time-resolved two-dimensional particle image velocimetry technique. The results suggest that separation of the boundary layer is weakly dependent of flow dynamics downstream from the separation location. Seemingly, the instability mechanism which governs the evolution of the LSB does not change significantly during the transitory regeneration process. The results contribute to characterize the dynamics of the LSB in transitory regime and offer original information about the phenomenon.*

Keywords: *Laminar Separation Bubble, Instability Hydrodynamics, Time Resolved Particle Image Velocimetry.*

1. INTRODUCTION

The presence of wake-LSB interaction in aerodynamic profiles can be associated with an increase of aircraft fuel consumption and reducing the airfoil efficiency, Ducosin et al. (2016), Hakan & Serdar (2018). There are a variety of situations where the wake-LSB interaction can occur, this work focuses on the scenario where there is a sudden variation on the level of flow disturbances upstream the bubble separation, for instance, in UAVs subjected to atmospheric gusts or in low-pressure turbines (LPT). The efficiency of a LPT strongly influences the engine fuel consumption, Wisler (1998) showed that a 1% improvement in the efficiency of a LPT improves fuel consumption by approximately 0.5-1.0 %. For long range aircrafts in cruise flight conditions an improvement of 1% in the efficiency of a LPT might result in a reduction of about 17% of total engine weight, or a reduction of 8% of engine cost. First studies devoted to LSB were reported in works of Gaster (1966) and Horton (1969). They provided a basis for subsequent models, as those developed by Dunham (1972) and Roberts (1980). These models were essentially based on empirical relationships that predict specific cases as pointed out by Serna (2013). Watmuff (1999) carried out a detailed experimental study of a two-dimensional LSB. In that work the stability characteristics of the bubble were investigated by introducing wave packets in the boundary layer. Watmuff (1999) suggested that within the wide range of flow conditions inside the LSB, the primary instability mechanism is related with Kelvin Helmholtz instability. A comprehensive review of the stability characteristics of a LSB can be found in the work Marxen & Rist (2010).

An interesting parameter is the bubble size and its sensitivity to variations of disturbance environmental condition upstream the separation point, Yarusevych, & Kotsonis (2017). The transient response of the bubble to sudden variation of disturbances is also interesting for the dynamics of the phenomenon and this is especially true for time periodic flow disturbances such as in the case of LPT. However, this transient response was scarcely investigated and the bubble regeneration from a situation without bubble to a quasi-steady regime have never been addressed in the literature. The simulation of this phenomenon is computationally expensive, especially if a parametric study is considered, which includes different levels of adverse pressure gradient. However, experimentally this is feasible.

Detailed experimental investigation of the transient response of LSB are not trivial due to the high temporal and spatial resolutions required for the measurement systems. This work aims to contribute for the physical description of the phenomenon by investigating transient response of a LSB subjected sudden changes in the perturbation conditions. High spatial and temporal resolutions are achieved by using high speed PIV systems with high resolution cameras to measure the flow in a water channel facility. To achieve these objectives a laminar separation bubble is induced on the surface of a flat plate and a vibration ribbon is employed to control the disturbance level upstream of the separation location.

2. EXPERIMENTAL SETUP

The experimental test campaigns were carried out in the water channel of the Laboratory of Fluid Engineering at PUC-Rio. The channel operates in a closed loop, and it has an open test section of 4x0.86x0.64 m (length x width x height). A Litron LDY-300 laser system was used as the light source. Two Phantom Miro M340 high-speed cameras were used to record the images, the acquisition frequency in burst mode was 50 Hz. Nikon macro lenses (105 mm) together with extenders allowed imaging a total area per camera of 600 x 2560 mm (height x width). The disturbance source consists of a vibrating ribbon. The system is based on the classic work by Schubauer & Skramstad (1948). The experimental arrangement is illustrated in figure 1.

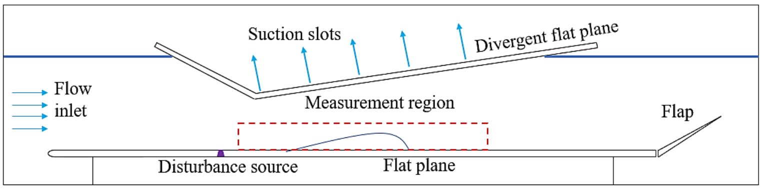

Figure 1. Schematic diagram of the test section.

The vibration ribbon has dimensions 1300 x 13 x 0.04 mm (length x width x thickness) and was positioned 4 mm high from the flat plate. The dimensions of the vibration ribbon were chosen based on some parameters of the most unstable Tollmien-Schlichting waves for the Reynolds number range of the flow at the predefined vibration ribbon operating position. The movement of the vibration ribbon was induced and modulated through the magnetic field generated by a 12V electromagnet. The signal modulation was controlled through an Arduino-Nano microcontroller and by LabView routines. The microcontroller also provides the trigger signal for synchronization with other equipment. Thus, with this system it was possible set up the amplitude, frequency, and total time of the disturbance generation.

3. PRELIMINARY RESULTS

The pressure distribution was indirectly measured through the free stream velocity distribution with and without the presence of LSB. To this end, the boundary layer was tripped near the leading edge to force a transition and consequently prevent the boundary layer separation. Velocity data from PIV measurements were collected immediately above the edge of the boundary layer, thus, it was possible to calculate the pressure distribution along the flat plate with and without the presence of LSB. The comparison of both pressure distributions is depicted in figure 2.

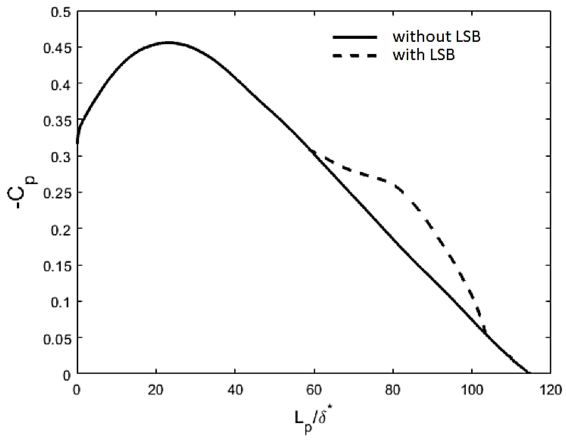

Figure 2. Pressure distribution for external flow with and without the presence of LSBs. Lp is the streamwise distance from the throat in the test section, δ^* is a displacement thickness in the separation point. Cp is the pressure coefficient.

Figure 3 shows the spectral content of wall normal flow fluctuations along the streamwise direction. The time series for each streamwise position was collected at a height corresponding to the inflection point of the base flow velocity profile. The spectra were obtained through the Fourier Transform and the Welch periodogram. These data were acquired with the vibration ribbon immersed in the flow, but switched off. The aim of this test was to observe whether the flow exhibited any dominant disturbance. This dominant disturbance frequency it would be used as a driving frequency for the vibrating ribbon, the idea is to minimize the energy of excitations required to remove the bubble. It is observed that highest energies are concentrated in the region of the reattachment point, where the separated shear layer is in the final stages of the transition regime. The Strouhal number vary in the range of $0.01 < St < 0.05$, which corresponds to fluctuations centered around 2.2 Hz. These fluctuations are related to the shedding vortex in the rear part of the bubble. Similar results were reported in the literature, for example in the work of Michelis et al. (2017).

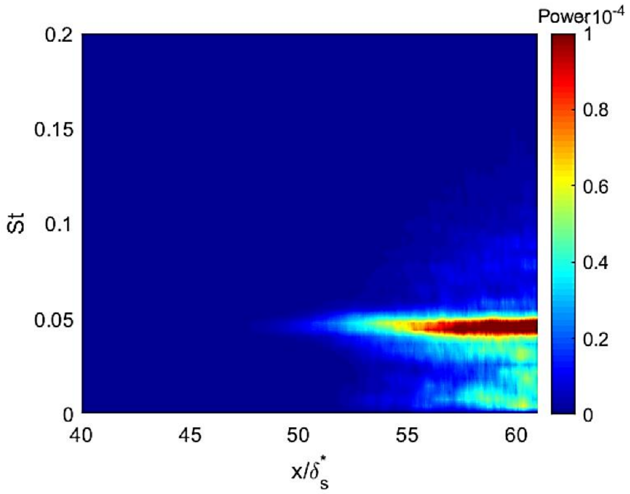

Figure 3. Streamwise energy contours of the field of wall normal velocity fluctuations, data acquired at the height of the inflection point for each streamwise position. δ_s^*: displacement thickness in the separation point. $St = \frac{f\delta_s^*}{u_0}$, u_0: edge velocity.

The flow field in the separation region was measured during the transient period from the instant when the disturbance source was switched off until the complete recovery of the separation bubble. At the initial instants the bubble was removed due to the high amplitude of remaining flow fluctuations induced by the source which needs some time to reach the measurement region. During its active period, the vibrating ribbon oscillation frequency was adjusted to 2.2 Hz which correspond to dominant flow disturbances, according to Figure 3. The amplitude of disturbances was established by adjusting the driving voltage of the source to the lowest value capable of eliminate the bubble. After 15 s of actuation and the complete disappearance of the bubble, the system was suddenly turned off. Just a few seconds after switching off the vibration ribbon, the bubble reappeared. This transient was measured 30 times, and the results presented in this section represents an ensemble average of these 30 events. Figure 4 shows the measured velocity fields corresponding to initial and final instants of the transitory regime.

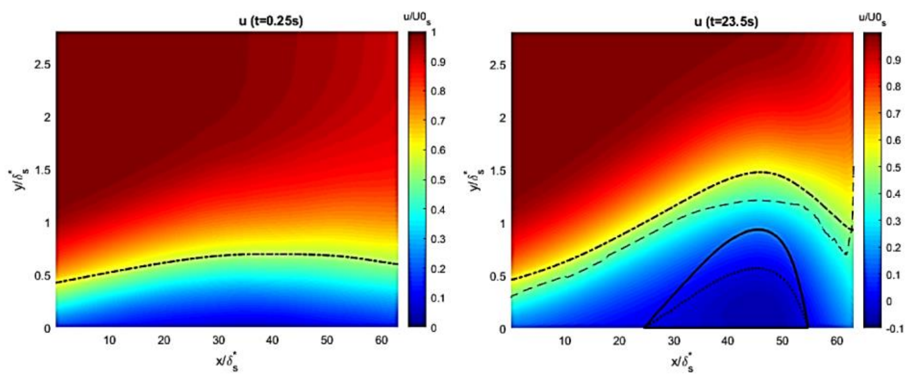

Figure 4. u-velocity contours at the initial (left) and final (right) instant of the transient regime. Solid line: Streamline ψ = 0; dotted line: velocity component, u=0; dashed line: inflection points; dot-dash line: displacement thickness δ^* .

The topological evolution of the bubble is illustrated in Figure 5 by the streamlines corresponding to ψ = 0. According to these results, at a given moment the bubble grows beyond its stationary length (approximately at 12.8s), as found in the work by Michelis et al (2017), this sudden expansion is known as bursting. High intensity vortex shedding was detected at instants when the bubble displayed its maximum length. Shedding of these vortices occur just before the bubble shrinks. This is merely a conjecture, based on some measurements and observations, which still demands further investigations.

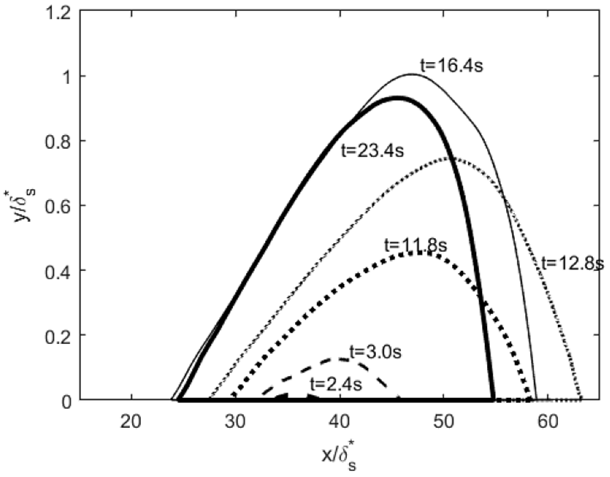

Figure 5. streamlines ψ = 0 at different times in the transient process, Bold solid line: final instant of the transient regime (Stationary condition).

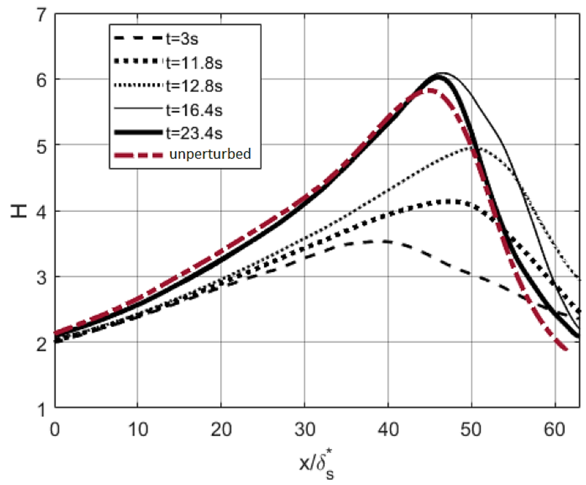

Figure 6. Shape factor H, in transient regime.

Figure 6 shows the evolution of the shape factor H, the streamwise coordinate is divided by the displacement thickness at the separation point. The maximum value of the shape factor varied along the streamwise coordinate during the transient period and follow the bubble topology. As the bubble approximates the quasi-steady regime the shape factor tends to gain amplitude and reach a maximum around x/δ_s^*=47. Qualitatively similar observations are reported in the work of Yarusevych and Kotsonis (2017). It is observed that the shape factor over the whole transient period occurs at almost constant H. This suggests that boundary layer detachment is weakly dependent on conditions downstream from the separation point.

4. CONCLUSIONS

In the present work a vibration ribbon it was chosen to excite the boundary layer to promote the complete removal of the separation bubble. After removal the bubble, the vibration ribbon was turned off and the transient regeneration process was measured, the experimental measurements were perform using the PIV technique. The bubble topology and dynamics observed in this work agreed with those presented in the literature. According to the results obtained, the shape factor at the separation point was practically invariant in the transient regime, this behavior indicates that, in this case, the boundary layer separation is weakly influenced by the flow dynamics downstream of the separation point. Additionally, it was found that during the regeneration period occur bubble bursting, thus, the extension of the bubble exceeds the mean reattachment point in the quasi-stationary case, however, in the final stages of the transition period the LSB completely recovers

It is worth mentioning that this work is still in development process, some future research will be focused on evaluating the results under the light of linear stability theories.

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6. RESPONSIBILITY NOTICE

The authors: Omar Elias Horna Pinedo, Pedro Bruno Pereira Panisset and Igor Braga de Paula are the only responsible for the printed material included in this paper.