Characterisation of the transient dynamics of the separated boundary layer reattachment using fluidic vortex generators

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Abstract The transient behavior of a high Reynolds number two-dimensional boundary layer flow encountering a massive separation is investigated. A spanwise array of pulsed round jets, located upstream of the separation region, is used as actuators. Spatial and temporal organization of the separation and reattachment processes are investigated using phase-locked PIV measurements in combination with the survey of wall friction along the separation region with the overall objective to develop closed-loop controllers. Different sets of parameters including free flow to jet velocities ratio, duty cycle and jets' frequency have been considered in the overall work. Only preliminary results for two cases are presented here.

1 Introduction

Extensive research has been done in the area of separated flows in order to understand the dominant flow structures in the separated shear layer and the general characteristics of the flow field. Since this flow phenomena is generally accompanied with negative effects on the performance, controlling the separation has gained in interest. For an equivalent efficiency, active control based on fluidic actuators is believed to offer the best potential in terms of performance and flexibility compared to passive control based on mechanical devices: these pave the way for controlling flow instabilities leading to separation for a minimal cost. Among active control devices, extensive studies have been conducted on pulsed vortex fluidic generators [3, 4, 5, 6] for which the flow rate needed to reattach the flow is smaller than for continuous actuation. These devices introduce vortices into the flow which interact with the natural instabilites of the boundary layer and reenergise the latter. Before attempting to develop any robust close-loop controllers, the flow physics under consideration must be characterised. In particular, the transient dynamics leading to reattachement or separation must be fully understood. This is the objective of the present work. The flow considered here is a high Reynolds number turbulent boundary layer encountering a massive separation in the presence of an abrupt change of the geometry on a two-dimensional ramp. Open-loop control is performed using an array of round jets located upstream of the separation. The influence on the transient dynamics of the flow of different control parameters is examined in details using phase-locked PIV measurements and surveys of the wall-friction.

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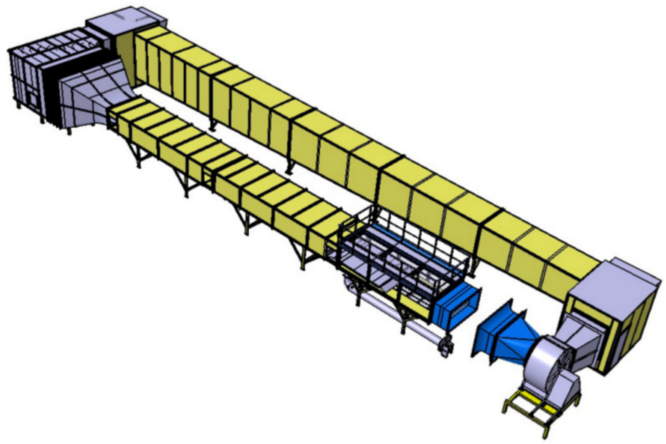


Fig. 1 Closed-loop boundary layer wind-tunnel in Lille.

2 Flow configuration & experimental set-up

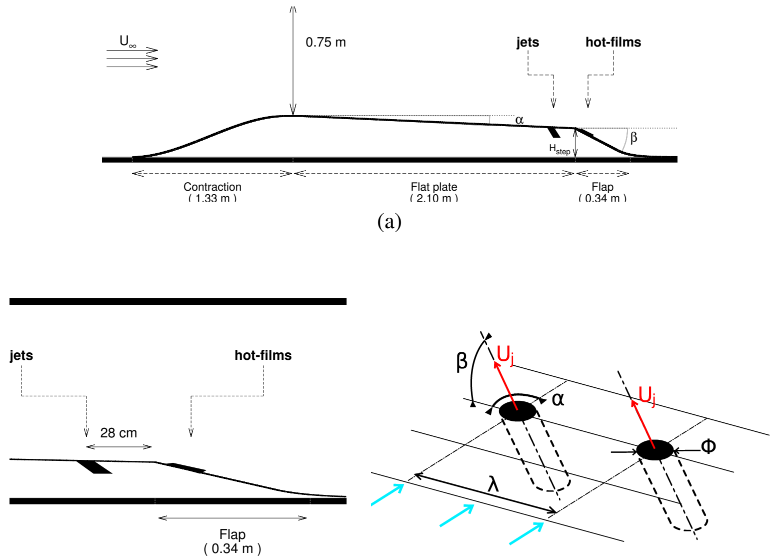
2.1 Flow & ramp model

The experiments are conducted in the closed loop boundary layer wind-tunnel at Laboratoire de Mécanique de Lille illustrated in figure 1. The working test section is $20m \times 2m \times 1m$. The maximum free stream mean velocity and turbulence level are 10 m/s and 0.3% respectively. Full details of the wind tunnel can be found in [1].

Beyond 14.4 m from the beginning of the test section, the boundary layer encounters a two-dimensional ramp. The ramp model is shown in figure 2(a). It is constituted of four parts: (1) a convergent part with smooth contraction ratio of 0.75, (2) an articulated 2.14 m long flat plate with an angle of -2° relative to the floor of the wind-tunnel, (3) a short flap with angle of $-22°$, and finally (4) a flexible plate ensuring smooth connection between the end of the flap and the floor of the wind tunnel. For the free flow velocities used in the present work and details below, and with the ramp configuration given previously, the flow separates at the sharp edge between the inclined flat plate and the flap. The heigh of the ramp at the separation line is 17.5 cm. A large separation bubble is observed along the flap, while the flow reattaches downstream on the floor of the wind-tunnel. At $U_\infty = 10$ m/s the boundary layer thickness just before separation is $\delta = 19$ cm.

2.2 Actuators & Control parameteres

A spanwise array of 22 round jets located upstream of the flap plays the role of actuators. Festo valves are used to generate continuous and pulsed jets. To fix the fow rate, a sonic throat with a 1.3 mm^2 area is implemented downstream of the valve. A tank located at the upstream level is used to maintain the main pressure constant. These actuators have been fully characterised by [7]. Figure 2(c) shows



(a)

(b) (b)

Fig. 2 (a) Schematics of the ramp model (AVERT). (b) Location of the hot-film sensor relative to the actuators. (c) Configuration and geometric parameters of the actuators.

the jets configuration considered in the present work: the jets are blowing in the upstream direction with an angle of $\alpha = 125°$ relative to the main flow direction, and $\beta = 35°$ relative to the wall-normal direction. The spacing between two consecutive jets is $\lambda = 0.43\delta$ and the exit jet diameter is $\phi = 0.03\delta$. This configuration generates co-rotating vortices which are further transported downstream, reenergising the boundary layer and forcing the later to more or less reattach along the wall.

The valves are driven by an Arduino micro-controller which allows us to generate pulsed or continuous actuation signals with a given duty cycle and frequency. In the perspective of developing closed-loop control, different control parameters have been considered. These include the frequency f of the pulsed actuation, the duty-cycle DC and the velocity ratio defined as VR $= U_j/U_{local}$ where U_j denotes the jets exit velocity and U_{local} the free stream velocity at the position of the jets (in our ramp configuration U_{local} = 12.3 m/s). The objective is to investigate first the receptivity of the flow with regards to different values of the parameters in the context of open-loop control. The overall test matrix is given in table 1 but only two cases will be presented in detail here further.

2.3 Measurements set-up

Two-component two-dimensional phase-locked PIV measurements are performed in a streamwise/wall-normal plane of the flow. The measurement plane is located in the middle of the ramp which also corresponds to half distance between two

<table>
<tr><th>U_∞ (m/s)</th><td>5</td><td colspan="12">10</td></tr>
<tr><th>VR</th><td>5</td><td colspan="4">3</td><td colspan="8">5</td></tr>
<tr><th>f (Hz)</th><td>4</td><td colspan="2">8</td><td>80</td><td rowspan="2">∞</td><td colspan="2">4</td><td colspan="2">8</td><td>10</td><td colspan="2">80</td><td rowspan="2">∞</td></tr>
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Table 1 Test matrix of the control parameters. Only cases VI and XIII are presented in the current paper.

consecutive jets. Four Hamamatsu camera with resolution of 2048×2048 px^2 each were used to cover the entire region of interest. This includes the region upstream of the separation where actuators are located, the region of separation and the region where the flow reattaches. To obtain good matching of final vector fields, the fields of view are overlaped and the meshing procedure developed by [2] is implemented. The entire boundary layer thickness is fully resolved. The laser sheet is provided by a Nd-Yag Laser with an energy of 400 mJ per pulse. A home-made code is used to process the PIV images to obtain the velocity vector fields. Full details of the optical set-tup can be found in [2].

In addition, hot-film sensors located along the inclined flat plate along the region of the separation bubble are used. The probe of interest for the present work is located 1.47 δ downstream of the array of actuators as illustrated in figure 2(b). The hot-film signals are sampled at 2kHz.

Both measurements are synchronised with the actuators thanks to a master clock. Sequences of 10 s are repeated. These sequences are divided into two phases corresponding to 5 s of forcing for flow reattachement (jets actuation turns on) and 5 s during which the flow is unforced and recovers a separated state (jets actuation turns off). For each set of parameters of the test matrix, 600 of these sequences are acquired to ensure statistical convergence. The duration of the two sequences has been chosen based on the results of [7] and allows the flow to reach stationary attached/separated states.

To perform temporal analysis of the transient dynamics during the separation and reattachement regimes of the flow, PIV measurements are operated under a phase-averaging procedure. Time instants (hereafter denoted phases) of the transition are selected and PIV fields corresponding to these phases are collected and averaged. It is noteworthy that by shifting in time the initial PIV phase, an increase of the time resolution of the final phase-averaged description can be obtained.

3 Experimental results

Two controlled configurations are here considered: continuous and pulsed blowing cases $XIII$ and VI respectively (see table 1).

3.1 Response to continuous blowing jets

The hot-film response for the continuous blowing jets case is shown in figure 3(a). These were obtained by averaging over 600 successive sequences of controlled and

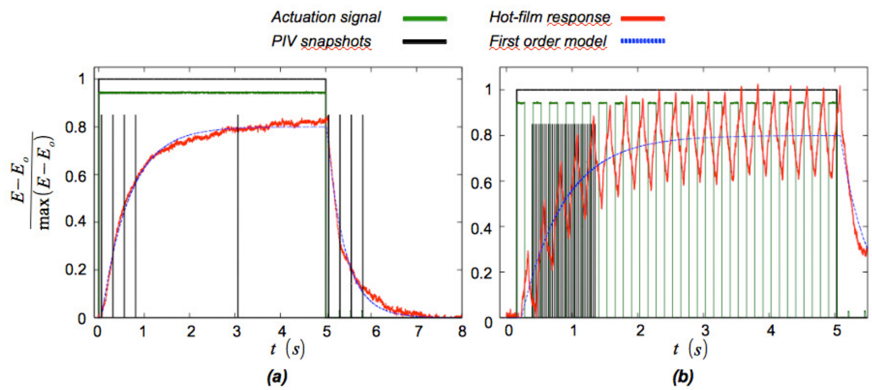

Fig. 3 (Red) Normalised averaged hot-film response to (a) continuous jets blowing and (b) pulsed jet blowing. (Green) actuation signal, (black) locations of the phase-locked PIV snapshots and (blue) first-order model response. $E(t)$ denotes the instantaneous hot-film response in Volt and E_o its offset value.

uncontrolled phases as described previously. The red line shows the hot-film response to jets actuation driven by excitation signal shown in green. The hot-film response is found to be characterised by two regimes corresponding to the control and uncontrolled phases. In the first regime, between $t = 0$ s en $t = 5$ s, the hot-film signal increases rapidly towards a plateau suggesting the flow has reached a stationary state. During this regime the actuation attemps to force the flow to reattach to the wall. When the actuation is turned off, at $t = 5s$, the hot-film response shows a rapid decrease towards a new plateau associated with the natural separated state of the flow. It is noteworthy that this happens with some time delay between the actuation and the flow response. Two time scales must be taken into account for this time shift: one due to the response of the valves to the excitation signal (the time between the raising edge of the actuation signal and the response of the valves is around 1.5 ms, so negligible compared to the characteristic times of the flow), and one due to the convection of the structures generated. The later is manifest in the hot-film response discussed here.

As the hot-film signal is noisy, it is necessary to average it on several cycles to remove this random noise. This was done for all the plots shown here. As described by [7], the transition between the separation and reattachment can be model as a first-order system. It is noteworthy that the transition towards separation can also be described by a similar system. While not described here, the different model parameters have been estimated for each test cases of table 4. These will be used in the follow-up work to develop a closed-loop control of the flow.

3.2 Response to pulsed blowing jets

3.2.1 Wall friction response

The hot-film averaged response for the pulsed actuation is shown in figure 3(b). The actuation signal consists now of periodic pulses. Again, the two regimes associated with reattachment and separation is manifest. During the controled regime (first 5 seconds), fairly periodic oscillations are observed with large amplitude and superimposed on a first-order response similar to that observed for the continous case. For each pulse, a vortical structure is generated by each jet. The oscillations observed in the hot-film response correspond to signature of the interaction of these convected structures with the boundary layer. The mark of the pulsed actuation can be noticed and correlated with the frequency of actuation. The time shift between the pulses and the oscillations is directly related to the distance between the hot-wire probe and the actuators as well as the convection velocity of the generated structures. As for the continuous case, the averaged response offers only an ideal picture of instantaneous responses. Again, while the reattachement and separation regimes can be guessed (figure not shown here), the response observed shows poor ressamblance with the averaged response. Despite this, a first approximation of the hot-film response to a given set of control parameters based on the averaged response may be obtained. In a real-time close-loop control perspective, the authors believe that a dynamical model of the hot-film response is more appropriate than a static one such as described for the continuous case previously. For this reason, a model identification based on an adaptative autoregressive moving average (AARMA) approach is implemented. While not detailed here, a result of this identification is shown in figure 4. As can be seen, the error between the original response and that predicted is negligible (less than 0.5%).

3.2.2 Flow-response

Instantaneous phase-averaged snaphots of the streamwise velocity components obtained from PIV are shown in figure 5. These cover the first 0.25s of reattachment regime highlighted in figure 3 by the hot-film response (first pulse of the actuation). The first snapshot (called phase 1) corresponds to the separated flow state. The following phases highlight the passage of a large convecting structure through the region of separation. A decrease of the reciculation bubble is first observed while the flow is “pushed” back to the wall (phases 2 to 5). When the large structure passes half of the flap (phase 6), the flow becomes almost fully reattached. The flow remains in this state until the structure attains the end of the flap (phase 7) after what a recirculation bubble reappears along the flap (phase 8) with a wall-normal dimension far less than for the fully separated state. As already mentioned, these 8 snapshots cover only one pulse of actuation. While not shown here, when looking at the response of the flow for the following pulses, the flow state remains between phases 7 & 8 shown in figure 5. A buble of separation is observed but with dimensions drastically reduced and located further downstream the flap.

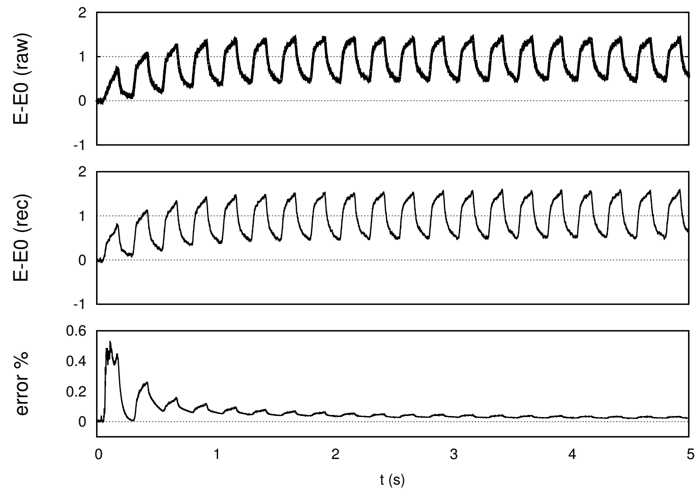

Fig. 4 (top) Original and (middle) predicted averaged responses of the hot-film. (Bottom) Error betwwen original and predicted responses. The raw signal is in Volts.

4 Conclusion

Preliminary results of a detailed survey of a separated turbulent boundary layer flow controlled with pulsed jets is presented. Synchronous phase-locked PIV measurements and wall-friction measurements using hot-film sensors are performed for different control parameters (jets frequency, duty cycle and velocity ratio). The spatial and temporal organization of the flow during transient regimes of separation/reattachement is examined. The preliminary results evidence a complex unsteadiness during separation and reattachement transitions. Further investigations are now needed. The overall database allows elements required for robust closed-loop control such as predictive model of the sensors response, low-order organisation of the flow and receptivity of the flow and sensor to control parameters, to be obtained. Spatial and temporal integral quantities will be extracted in order to better understand the role of the actuation on the boundary layer, and particularly the influence of the actuation parameters. Due to the complex dynamics of the transient regimes, advanced analysis is necessary to extract local informations on the flow transition from separated to attached and vice versa. At the end, this information will be used to develop robust closed-loop controllers.

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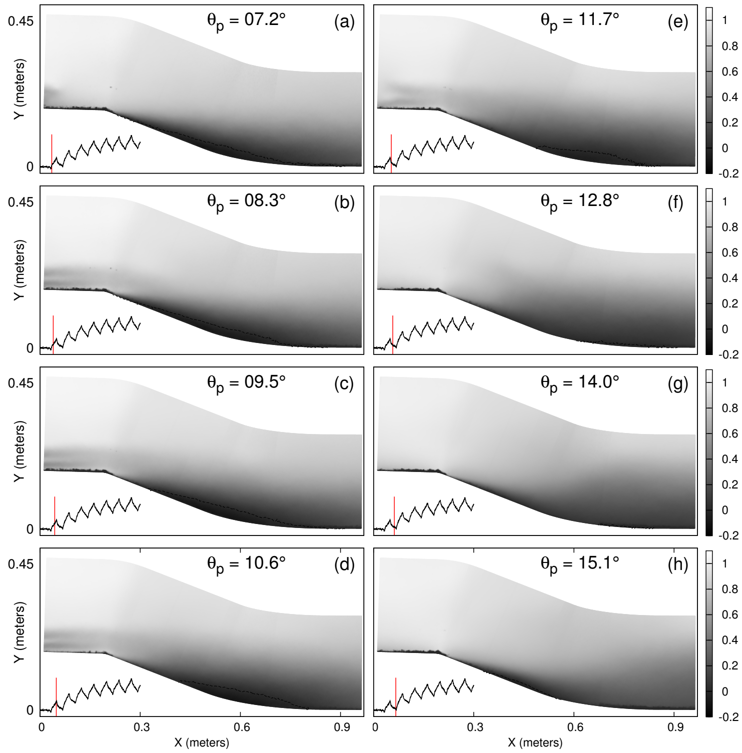

Fig. 5 Phase-averaged flow response (streamwise velocity component) to pulsed case XIII during the first eight phases. For each subfigure, the location of the phase relative to the excitation signal and hot-film response is shown in the bottom-left corner.

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