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EXPERIMENTAL OPEN-LOOP AND CLOSED-LOOP CONTROL OF A MASSIVE SEPARATED BOUNDARY LAYER AT HIGH REYNOLDS NUMBER

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INTRODUCTION

Developing flow control strategies has been an important effort in the last decades to avoid separation of boundary layers mainly for aerodynamic gains. Active flow control with fluidic actuators is nowadays a well-known solution to remove or reduce significantly the separation. Pulsed actuation has been particularly studied as a technique using less flow rate with similar performances as continuous blowing [3, 5, 6, 8]. In order to increase the control performances (precision, dynamics, resistance to flow perturbations...), feedback closed-loop control can be chosen [1, 9].

The present study addresses open-loop transient characterization and closed-loop control of a mostly two-dimensional turbulent boundary layer with massive separation under a pulsed fluidic actuation.

EXPERIMENTAL SETUP

The experiments are conducted in the LML boundary layer wind tunnel in Lille, France. A two-dimensional ramp is used in the wind-tunnel to generate a mild adverse pressure gradient and force the separation of the incoming boundary layer (fig. 1). At a wind-tunnel velocity of $U_\infty = 10$ m/s, the boundary layer thickness is $\delta = 0.19$ m and the Reynolds number Re_θ based on the momentum thickness θ just before the flap leading edge is up to 12600. The separation is massive and the separation length is $L_{sep} = 0.59$ m, using the backflow coefficient χ criteria [4].

The control is realized with 22 round fluidic jets distributed in the spanwise direction upstream of the separation line. The configuration of the jets generates co-rotating vortices which re-energise the near-wall region, and force the flow reattachment, depending on the actuation parameters of the jets. More details on the experimental setup can be found in [2, 7].

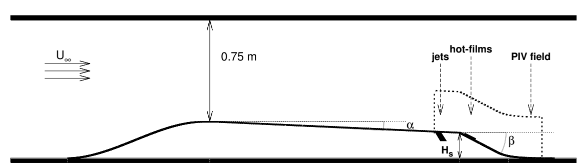

Figure 1: 2D-sketch of the AVERT ramp used for the experiments.

OPEN-LOOP EXPERIMENTS

The transition between the separated and attached flows is studied in details. Simultaneous velocity and friction gain measurements are performed during this transition. Phase-averaged velocity fields are obtained from 2D-2C PIV oriented in the streamwise direction and normal to the wall (fig. 2). Hot-film sensors placed along the separation region provide instantaneous measurements representative of the skin-friction. These friction gain measurements allow firstly to have time-resolved informations on the transition, not accessible with

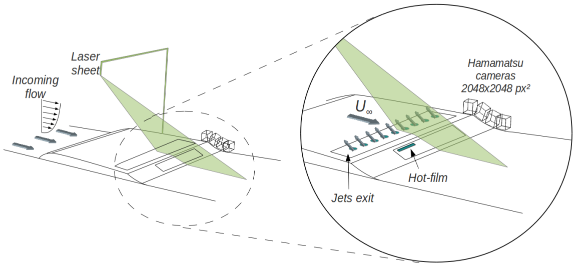

Figure 2: 3D-sketch of the AVERT ramp and 2D-2D PIV setup used in the study.

low-speed PIV, and then to use these sensors as real-time inputs for the closed-loop experiments. Continuous and pulsed actuations are considered here and the effect of main actuation parameters (velocity ratio VR, frequency f, duty cycle DC) on the control efficiency is studied.

These informations, particularly from the hot-film sensors, are considered as representative of the flow state during the transition. To design efficient closed-loop control, accurate models of transient dynamics, particularly the reattachment process, are necessary. Characteristic times of the transition (rising time, delays) are firstly obtained by fitting a first-order law on the hot-film sensors responses. For a better approximation of the flow dynamics during the reattachment, advanced models are also considered, based for example on the separation length or using input-output polynomial models.

CLOSED-LOOP EXPERIMENTS

Based on these models, closed-loop control had been realized. The experimental setup, specific for closed-loop control, is presented in figure 3. Instantaneous friction gain from hot-film sensors is the measured output. The duty cycle for the jets pulsed signal is the control input generated with these informations. Several closed-loop algorithms had been tested. Feedback laws based on P, PI and PID algorithms have firstly been performed. The controller objective is to minimize the difference between the hot-film sensor signal and a target defined by the users. The behaviour and performances (mainly, small overshoot and high response speed) have been modified by means of an adequate tuning of the parameters (P, I and D gains).

Optimal LQR control (Linear-Quadratic Regulation) is also considered. The actuation cost can now be taken into account in the controller through the minimization of a cost function. The influence of sensors noise on the closed-loop control performances can also be reduced by using estimators. Kalman filters are implemented in order to estimate the separation length from informations obtained from hot-film sensors and the duty cycle. A closed-loop control (named LQG - Linear-Quadratic Gaussian) is realized using this estimation.

Unavoidably, uncertainties of the controlled system can appear. Dynamical models are not perfectly defined and the incoming flow can be perturbed. Consequently, control performances can be deteriorated under these uncertainties. A robust control based on $\mathcal{H}_\infty$ synthesis is realized here in order to reduce the influence of these uncertainties on the control performance. The objective is to maintain the control robustness for a system submitted to random perturbations and system uncertainties. The robustness of few controllers was tested experimentally with perturbing the incoming boundary layer before the leading edge.

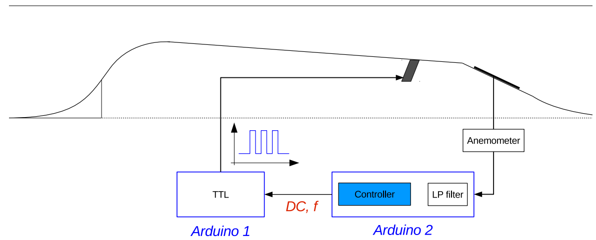

Figure 3: Experimental setup for closed-loop experiments.

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