Experimental closed-loop control of a detached boundary layer at high Reynolds number

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A large variety of flow control strategies has been used in the last decades to avoid separation of boundary layers for, as major concern, aerodynamic benefits. The paper addresses closed-loop control of a quasi two-dimensional turbulent boundary layer with massive separation. The experiments are conducted in the LML boundary layer wind tunnel in Lille. Special attention is paid to the transient dynamics between the separation and reattachment regimes. For the control itself, 22 round air jets distributed in the spanwise direction upstream of the separation line are used as actuators. The jets generate co-rotating vortices which re-energise the near-wall region, and force the flow to reattach more or less depending on the actuation parameters.

The transition between the separated and the attached flow is first examined. Hot-film sensors placed along the separation region are used to obtain an instantaneous measurement representative of the skin-friction during reattachment regime. Both continuous and pulsed actuations are considered. The actuation parameters considered for the present study are: the velocity ratio between the jets exit and the freestream, the jets' frequency, the duty cycle, and the freestream velocity. In order to quantify the sensitivity of the flow with regards to these parameters, different sets of values are considered.

The hot-film responses are here considered as a good metric for the flow state (fully/partially attached or fully detached). The control strategy implemented therefore leans on the possibility to predict hot-film responses when the flow is subjected to various forcing/actuation. Modelling of the hot-film responses is thus effected for the range of control parameters covered. At first, characteristic time constants (rising time etc...) are determined by fitting a first-order law. Secondly, time-series models identification (ARMAX, Box-Jenkins, etc.) and dynamical systems are built in order to have a better approximation of the transient dynamics than the first-order model.

From these models, closed-loop experiments are performed. Closed-loop feedback based on P, PI & PID algorithms with the duty cycle as control input are first implemented to serve as a reference. The duty cycle is normalized and estimated from the difference between the friction wanted and the measure of the hot-film sensors. Optimal control (LQR) is also considered. The algorithm is aimed at the maximisation of the gain in friction with minimal flow rate input. The various time delays of the system "actuator+flow+sensor" are also taken into account for the control design.

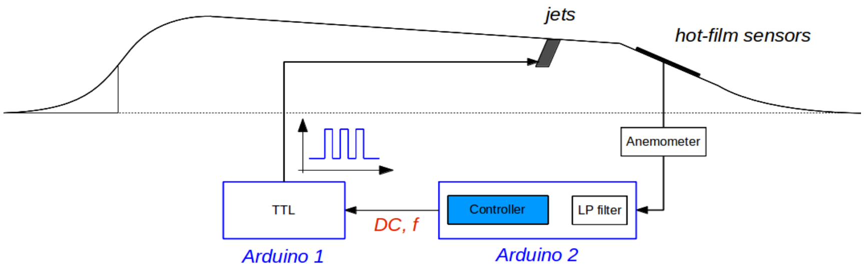

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Figure 1: Closed-loop control experiment based on pulsed jets.