Flow separation control using optical feedback

V. PAREZANOVIC[a] , A. SPOHN[a] , L. CORDIER[a]

a. Institut PPRIME, CNRS - Université de Poitiers - ENSMA, UPR 3346,
Département Fluides, Thermique, Combustion, CEAT, 43, rue de l'Aérodrome,
F-86036 Poitiers Cedex, France
vladimir.parezanovic@univ-poitiers.fr

Abstract

Flow separation induced by adverse pressure gradients leads in many engineering applications to severe losses and restrictions of operation range. For example, detached flow on wings leads to drag increase and lift decrease, while compressor stall can lead to thrust reduction accompanied by dangerous unsteady loads. The mitigation of flow separation remains, therefore, an ongoing challenge and a quintessential goal of flow control.

Frequently, simple passive control devices, as in the example of vortex generators, are used to energize a boundary layer to delay or prevent separation. While such means are easy to implement and require no external energy input, they are completely unable to adapt to variable flow regimes and could have negative effects outside their design point. The situation is similar for active flow control devices which operate steadily, for example in the case of periodic forcing by pulsing jets. If the operation point changes the fixed actuation frequency will mismatch the new flow conditions and efficient separation control will not be possible.

To overcome this drawback, effective closed-loop control systems have been increasingly tested in recent years (Pinier et al.*, 2007; Pastoor* et al.*, 2008; Wiltse & Glezer, 2011; Parezanović* et al.*, 2014). A key interest in closing the control loop is its implied capacity for adapting the actuation to changes in the flow conditions or external perturbations thus improving the robustness of the control (Aström & Murray, 2010). Until recently, sensor feedback data has mostly originated from local measurements: pressure sensors, hot-wire probes, etc. Some of the most recent experimental applications of closed-loop control have begun using optical sensors, such as real-time PIV flow fields to provide feedback data (Gautier & Aider, 2013, 2015).*

In the present study we propose a new technique of using optical sensors, based on Lagrangian tracers obtained with help of the controlled release of hydrogen bubbles. The processing of the real-time flow visualizations is based on image processing of the tracer distribution, without the time consuming analysis of the velocity field. Only simple hardware and software components are needed.

To facilitate the use of time-resolved flow visualisations the experiment is carried out in a water tunnel. The experimental set-up is schematically shown in figure 1. The goal of our experiments is to control the laminar separation bubble caused by the adverse pressure gradient along a smooth diverging ramp which joins an upstream flat plate of 100mm length with a sharp leading edge. The Reynolds number of the flow based on the length the upstream flat plate is varied between 8000 and 12000. The flow is visualized by pulsed columns of hydrogen bubbles (Schraub et al.*, 1965) in combination with white light diodes for the illumination. A greyscale USB camera (Point Grey flea3) records the flow region with the separation bubble at a rate of 10 Hz. To allow local and flexible control we employ a wire of 0.13 mm diameter which is supported by an oscillating holder. The wire crosses the whole span of the ramp at about 100 mm downstream of the leading edge of the flat plate inside the bottom third of the boundary layer thickness. Actuation is performed by oscillating the wire in the vertical sense across the boundary layer. Without vertical oscillation the wire has no impact on the separation bubble. The objective function for control is defined as the area of the recirculation region after flow separation, and the goal is to minimize it. The area is measured directly from the grey-scale images of the seeded flow. Since the hydrogen bubbles are released from a vertical wire in the mid-plane of the test section, fixed upstream of flow separation, only a few tracer bubbles enter the separated flow region by the unsteady reattachment process. The obtained tracer distribution, therefore, produce a high contrast image of the separated flow region with essentially no markers. This allows us to measure the size and the shape of the recirculation region at each time step directly by image processing.*

In order to adapt the actuation to the varying flow conditions it is crucial to identify the modes of the flow and their specific frequencies. Open-loop control experiments confirm that the best actuation frequency for minimizing the objective function, lies around the natural frequency for the Kelvin Helmholtz instability of the separated shear layer. In order to detect this frequency for any flow condition, we perform Singular Value Decomposition of each visualization image. In recent years SVD has been used frequently as a tool for data reduction in fluid mechanics (Bright et al.*, 2013). In our experiment, the eigenvalues obtained by SVD can be used to represent the fluctuations of different spatio-temporal scales found in the flow. The study of the natural flow for different Reynolds numbers, confirms that SVD is successful at registering the frequency of the shear layer instability. Also, in the case of the open-loop control, SVD can clearly discern the frequency of actuation.*

It is therefore required to select an eigenvalue which registers the fluctuations of the natural Kelvin-Helmholtz mode and send it as the sensor signal to the closed-loop controller. The actuator wire is displaced proportionally to the fluctuation of the selected eigenvalue. When the values of the resulting objective function values are compared to those of the best periodic forcing, the efficiency is found to be similar as in open-loop case. In fact, the closed-loop control produces quasi-periodic actuation around the natural frequency detected by SVD. However, the benefit of closed-loop control is best illustrated be testing the robustness of the system. When changing abruptly the flow velocity in the tunnel the closed-loop control automatically adapts to the new natural

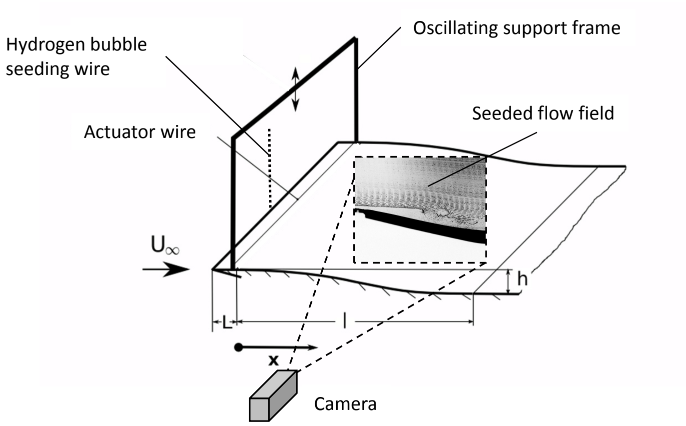

Figure 1: Schematic of the experimental set-up. The free-stream velocity U_∞ is directed from the left to the right. The ramp is composed of two sections: a horizontal upstream part of length L = 10 cm with a sharp leading edge, followed by the divergent section of length l = 60 cm and height h = 6 cm. The picture in the central plane shows a typical visualisation obtained with the hydrogen bubble technique. The bubbles were released periodically from a 0.05 mm thick wire made of stainless steel. The instantaneous flow images captured by the USB camera are analysed in real-time by SVD to impose the control action to the oscillating wire actuator.

frequency of the separated shear layer and thus keeps the region of the separated flow region minimal. This is confirmed even in the case of a single long acquisition, during which the Reynolds number has been changed several times. The time needed for the controller to adapt is very short (a couple of vortex shedding cycles), and during this time, there is no measurable negative effects on the recirculation region size. Moreover if the visualization is examined, this process appears continuous.

The eigenvalue-based feedback control shows very robust behaviour. The SVD technique used to distil the relevant frequencies is both efficient in terms of resources needed for real-time operation, as well as in terms of frequency detection in both the natural and the controlled states of the flow. Considering that the differences in flow topology between these two states can be large (recirculation region can be reduced to as low as 5% of the natural value), a spatially localized sensor would be hard (if not impossible) to optimize for both states. The spatial integration inherent in the SVD allows the controller to remain aware of the relevant signal, regardless of such changes.

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Mots clefs : Shear flows, Flow separation, Closed-loop control, Kelvin-Helmholtz instability, Singular Value Decomposition

References

ASTRÖM, K. J. & MURRAY, R. M. 2010 *Feedback systems: an introduction for scientists and engineers*. Princeton university press.

BRIGHT, I., LIN, G. & KUTZ, J. N. 2013 Compressive sensing based machine learning strategy for characterizing the flow around a cylinder with limited pressure measurements. *Phys. Fluids* **25** (12), 127102.

GAUTIER, N. & AIDER, J.-L. 2013 Control of the separated flow downstream a backward-facing step using real-time visual feedback. *Phil Trans R Soc A* **469**.

GAUTIER, N. & AIDER, J.-L. 2015 Frequency-lock reactive control of a separated flow enabled by visual sensors. *Exp. Fluids* **56** (1), 1–10.

PAREZANOVIĆ, V., LAURENTIE, J.-C., FOURMENT, C., DELVILLE, J., BONNET, J.-P., SPOHN, A., DURIEZ, T., CORDIER, L., NOACK, B. R., ABEL, M., SEGOND, M., SHAQARIN, T. & BRUNTON, S. L. 2014 Mixing layer manipulation experiment: From open-loop forcing to closed-loop machine learning control. *Flow Turbul. Combust.* **94** (1), 155–173.

PASTOOR, M., HENNING, L., NOACK, B. R., KING, R. & TADMOR, G. 2008 Feedback shear layer control for bluff body drag reduction. *J. Fluid Mech.* **608**, 161–196.

PINIER, J. T., AUSSEUR, J. M., GLAUSER, M. N. & HIGUCHI, H. 2007 Proportional closed-loop feedback control of flow separation. *AIAA journal* **45** (1), 181–190.

SCHRAUB, F. A., KLINE, S. J., HENRY, J., RUNSTADLER, P. W. & LITTELL, A. 1965 Use of hydrogen bubbles for quantitative determination of time-dependent velocity fields in low-speed water flows. *J. Fluids Eng.* **87** (2), 429–444.

WILTSE, J. M. & GLEZER, A. 2011 The effect of closed-loop feedback control on scalar mixing in a plane shear layer. *Exp. Fluids* **51** (5), 1291–1314.