5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

Optical feedback for closed-loop flow control systems

A. Spohn[1]* and V. Parezanović[2]

[1] Institut PPRIME, CNRS - Université de Poitiers - ENSMA, UPR 3346, Département Fluides, Thermique, Combustion, F-86036 Poitiers Cedex, France

[2] Department of Aerospace Engineering, Khalifa University, 127788, Abu Dhabi, United Arab Emirates

*corresponding author spohn@ensma.fr

Abstract

Recent progress in data acquisition and analysis led to the development of a whole plethora of closed-loop flow control strategies for engineering applications. Due to real-time constraints and availability most of such control systems are provided with electrical feedback data obtained from local measurements with hot-wire probes, pressure sensors etc. Such local measurements allow only restricted access to the instantaneous global flow dynamics. In this study we use instead flow visualizations obtained with the hydrogen bubble technique to extract sensor signals from the global flow field. The method is tested inside a water tunnel with the help of the canonical flow along a slowly diverging ramp which leads to smooth laminar flow separation. The goal is to improve the pressure recovery by reducing the size of the separated flow region. Images of the periodically released hydrogen bubbles are processed to extract feedback signals which allow the control unit by means of an implemented control law to determine the control signal for the mechanical actuator. Although limited to water flows at low speeds of the $O(10^{-1})$ m/s, the hydrogen bubble technique turns out to be a highly versatile candidate for future tests of different data-driven control approaches.

1 Introduction

In many engineering applications closed-loop flow control has become a promising option to improve the overall efficiency and to extend the operation range (Pastoor et al. 2008). According to Aström and Murray (2010) one of the key interests in closing the control loop lies in its capacity to ensure the necessary stable system dynamics and responsiveness by adapting the actuation to perturbations and changing flow conditions. The functionality of such closed-loop control systems strongly relies on the use of suitable sensor feedback data. Until recently, sensor feedback data have mostly originated from local measurements obtained with hot-wire probes, pressures sensors or wall-shear stress gauges. However, without complementary data on the flow field, it remains a very challenging task to choose the most appropriate location of such local sensors. In the absence of dynamically relevant feedback signals the control objective can not be achieved. Optical feedback with flexible selection of the region of interest constitutes an interesting alternative. In a recent experimental study on closed-loop control behind a backward facing step, Gautier and Aider (2013, 2015) begun to use real-time PIV measurements as optical sensors to provide feedback data. Thereby the computation of the velocity field in real-time turned out to be computationally expensive, needing powerful GPU processing units. In the present study we propose alternatively to use the hydrogen bubble technique, introduced by Clutter and Smith (1961), among others, to extract feedback signals from the instantaneous flow field. This technique furnishes by means of the controlled release of hydrogen bubbles, continuously advancing Lagrangian tracer distributions. The images of these tracers distributions can be processed in real-time to extract feedback signals without the need for time expensive correlations. Both, the seeding of the flow with hydrogen bubbles and the use of image processing techniques requires only simple standard hardware and software components.

2 Experimental set-up

The experiments were carried out in a low-speed water tunnel to facilitate time-resolved flow measurements by optical means. The test section with a free surface is 2.1 m long, 0.5 m wide and 0.35 m high. The freestream velocity can be varied between 0.05 m/s and 0.5 m/s. To obtain flow separation under canonical conditions the flow is forced to follow a specific wall contour which starts 0.6 m downstream of the test section inlet and divides the flow in an upper and lower stream. Figure 1 shows a schematic of the global arrangement with the smooth ramp geometry. A flat plate with sharp leading edge insures on a length L = 100 mm the development of a laminar boundary layer with zero pressure gradient. The shape of the adjacent diverging ramp with height h = 60 mm and length l = 600 mm is described by a polynomial of order 7 and ensures, like in the case of the study by Bao and Dallmann (2004), the formation of a laminar separation bubble under the influence of an adverse pressure gradient. The ramp model has a width of 498 mm leaving two lateral 1 mm wide gaps between the ramp and the tunnel wall. On the downstream side of the ramp a splitter plate separates the upper and lower flow up to the outlet of the test section. In this way the stagnation point on the sharp leading edge could be controlled by adjustable pres-

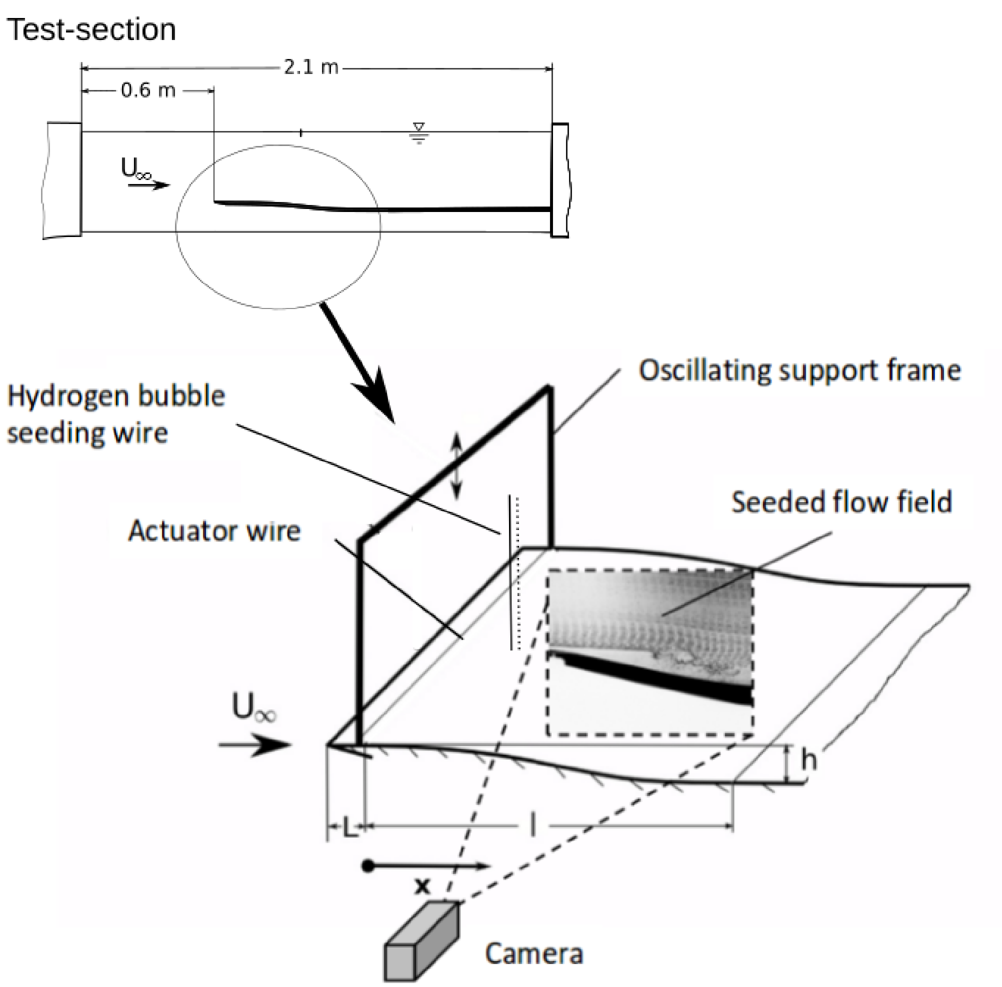
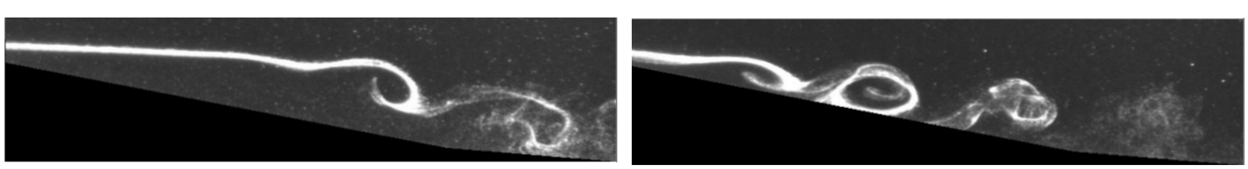


Figure 1: Experimental arrangement with smooth ramp and oscillating actuator. The flow in the middle plane is visualized with the hydrogen bubble technique and captured by USB cameras. Image processing is used to extract different optical feedback signals as input for the controller unit. The output of this unit furnishes the actuator command signal.

sure losses at the outlet of the upper stream. The Reynolds number $\mathrm{Re}=U_\infty L/\nu$, based on free stream velocity U_∞ and the kinematic viscosity ν of water varied between $O(10^3)$ and $0(10^4)$.
In most experiments the hydrogen bubbles were released from a vertical 0.05 mm thick stainless steal wire which could be placed at different axial positions along the center line of the ramp. At both ends the wire was connected to the negative potential of a 80 Volt DC power supply to produce by electrolysis hydrogen bubbles. This connection could be switched on and off by an in-house designed transistor switch with a digital input channel which allows to apply highly flexible digital timing diagrams with frequencies up to 1 kHz. The particular layout of this switch made it also possible to invert the polarization of the wire during specified time intervals to clean the wire and maintain a high bubble quality over observation times of the order of ten's of minutes. In some experiments the seeding technique was modified using instead of the straight wire a small oval loop with 2 mm principal diameter. The loop was fixed vertically on the wall of the ramp about 10 mm downstream of the separation line. Similar to the case of tilted wires used by Clutter and Smith (1961) the hydrogen bubbles accumulate on the top of the loop and are continuously convected with the flow close to the wall to form a streak line.
The hydrogen bubbles were illuminated by rows of LEDs under a mean angle of 55° with respect to the vertical plane to maximize the reflected light captured by FLEA3 USB cameras. The acquired images were then processed by a standard desktop computer to compute, according to the chosen control law, the control signal for the actuator. All necessary programs were developed in the LABVIEW environment. Depending on the extension of the region of interest (ROI) used to fabricate the sensor signal, the control-loop could be operated with frequencies up to 30 Hz, while the natural frequencies inside the flow field remained of O(1) Hz.
The mechanical actuator consisted of an oscillating wire similar to the arrangement used by Kaiser et al. (2013). A vertically oscillating fork spans a horizontal nylon wire with 0.13 mm diameter over the whole width of the ramp. The immobile fork was positioned at about 90 mm downstream of the leading edge and 3.5 mm above the wall. Its presence no measurable impact on the separation bubble. However, with vertical oscillations of the wire imposed by a electric servo (RS-2 modelcraft) the produced perturbations modify the recirculation zone visibly. The servo itself received command signal by a digital output channel form the control unit. The actuator frequency ranged between 0.1 and 3 Hz and the oscillation amplitude was limited to maximal 1.5 mm so that the wire remained well inside the boundary layer.

3 Results

Fig. 2 shows an example of the effect of periodic forcing without optical feedback on the laminar separations bubble at Re = 7900. The hydrogen bubbles were released from a looped wire close to the wall. Without switching the voltage on and off the continuously released hydrogen bubbles form a streak surface which surrounds the separated flow region. In Fig 2*(a)*, without periodic forcing, the tracer progresses in the upstream part of the bubble nearly horizontally. Further downstream naturally developing flow instabilities deform the steak surface and finally the tracer is rolled up around Kelvin-Helmholtz vortices. The presence of hydrogen bubbles close to the wall in this region indicates periodic reattachment of the flow. With periodic forcing, shown in Fig. 2*(b)*, the tracer rolls-up much more rapidly leading to a reduced length and height of the separated flow region.



(a) (b)

Figure 2: Visualization of the separated flow region with the hydrogen bubble technique at Re = 7900: *(a)* natural case without forcing, *(b)* with periodic forcing at $f_{act}=0.56\,Hz$ and amplitude 1.5 mm.

To explore the potential of the hydrogen bubble technique as optical sensor we tried in a first approach to define an objective function which allows to select the best actuation frequency with open-loop control. For each actuation frequency f_{act} we acquired 500 images at a frame rate of 10 *Hz* and averaged the pixel values to build a mean image with normalized light intensities. By thresholding this mean image we could determine as objective function the surface J of the dark area between the wall and the mean position of the surrounding bright streak surface, which represents a measure for the dimensions of the recirculation bubble. In agreement with previous findings by Kaiser et al. (2013) forcing at the natural shedding frequency f_{KH} of the separated shear layer leads to the smallest area J_n of the recirculation zone. Fig. 3 shows the obtained mean light intensities and the corresponding evolution of the ratio J/J_n as a function of actuation frequency f_{act} for two different actuator mean position above the wall. The vertical mean position y_0 of the actuator wire has no significant impact as long as it remains in the lower half of the boundary layer thickness.

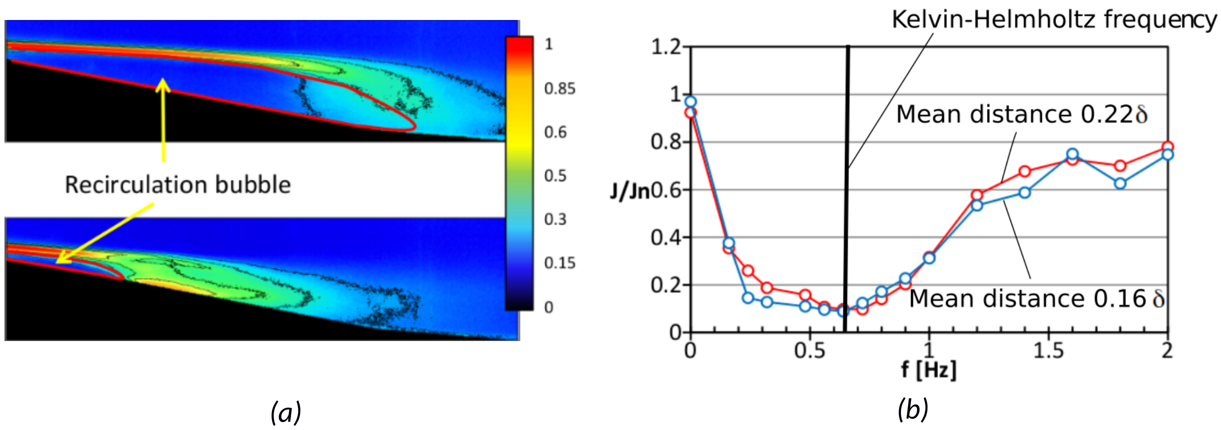


Figure 3: Impact of periodic forcing at $\mathrm{Re} = 8000$. *(a)* Distribution of normalized light intensity, above uncontrolled, below forcing with natural frequency, *b)* Evolution of the non-dimensional objective function J/J_n .

Unfortunately this objective function needs to compute mean values out of hundreds of images in order to extract the position of the reattachment region with sufficient precision. Instantaneous measurements are not possible since the unsteady character of the flow in the reattachment region leads to blurred boundaries, which hinder the determination of instantaneous recirculation areas. Alternatively we tried to use Singular Value Decomposition (SVD) to analyze the dynamic modes inside the flow by means of their contribution to different light intensities modes. Although SVD could be carried out in real-time the identification of the dynamically most important modes turned out to be challenging. The mode with the highest light intensity is not necessarily the mode with the highest dynamical impact. To overcome this difficulty we tried to extract more robust information from the tracer distribution. Fig. 4 illustrates the employed procedure. If the region of interest (ROI) remains restricted to flow domains with continuously crossing time-lines, then the light intensity profiles along the x-axis show a succession of well distinguishable peaks. By measuring the pixel distance between the individual maxima it is possible to extract the instantaneous distribution of the x-component of the velocity field with a high signal to noise ratio. Both the spatial evolution of the velocity component and its local temporal evolution can be measured in this way.

In a further step the ROI can be reduced to a small area in order to select a particular dynamic behavior inside the flow as feedback signal. Fig. 5 shows an example how selecting a specific ROI location impacts on the frequency content of the feedback signal and, hence, also on the actuator displacement. The importance of the subtle choice of the ROI becomes particularly evident in figure 3 *(b)*. Feedback signals with frequency contents far from the natural Kelvin-Helmholtz frequency f_{KH} can not be expected to obtain the best control results. Although the versatility of the hydrogen bubble technique itself strongly facilitates the research for best locations of the optical sensing, it remains a time consuming iterative task.

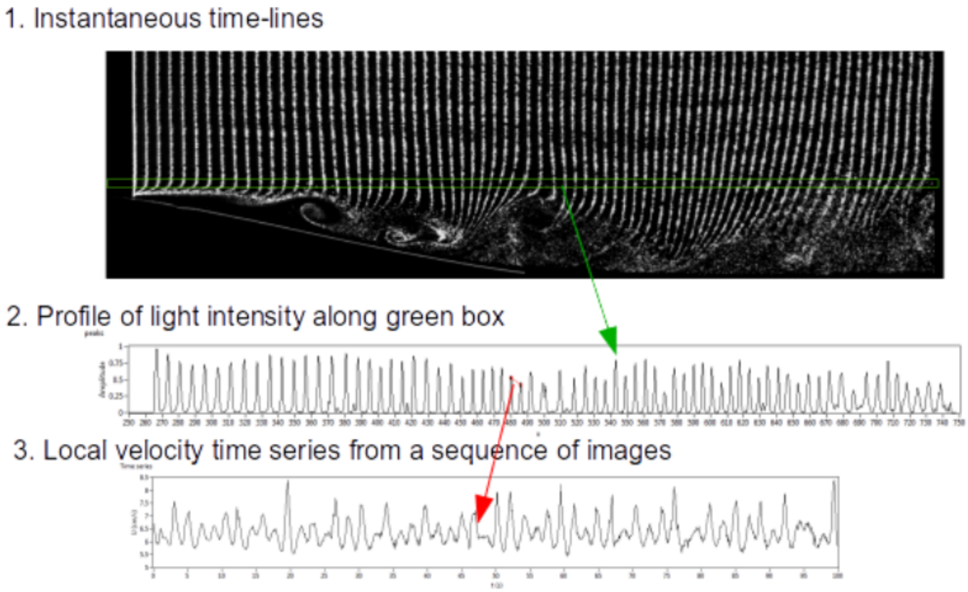


Figure 4: Determination of the axial velocity components using the time-line distribution at Re = 8000. The distance between peaks in the light intensity profile indicates the instantaneous distribution of the horizontal velocity component. At a given location the temporal sequence of peaks contains the frequency content of the streamwise velocity at this position.

(a)

(b)

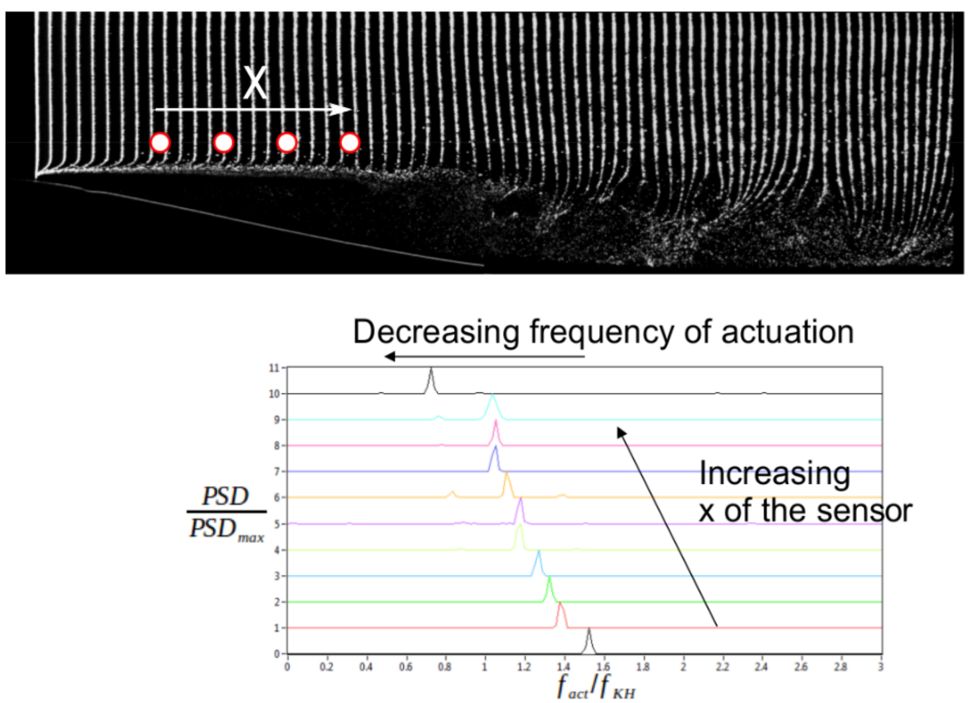


Figure 5: Determination of the characteristic frequencies inside the flow at different locations along the separated shear layer for the uncontrolled flow at Re = 8000. *(a)* Different positions of the ROI along the x direction,
(b) Decrease of the characteristic frequencies with increasing distance x.

4 Conclusion

The experiments presented in this study demonstrate that the hydrogen bubble technique represents a highly versatile option to obtain optical feedback for closed-loop control. It furnishes at the same time visualizations to identify regions which potentially interesting dynamics and the possibility to evaluate the suitability of the sensor signal by classical image processing algorithms. Thereby the information contained in the progression of pulsed time lines exhibit the best signal to noise ratio, while the use of streak lines can give raise to unacceptable noise levels. For future tests of data-driven control systems optical sensing strongly relies on the longtime reproducibility of the seeding conditions, in particular in cases with learning phases such as reinforcement learning and genetic programming. For these challenging tasks PIV measurements need tracer particles with minimal buoyancy, while the hydrogen bubble technique needs to limit the degradation of the bubble production due to polarization of the electrodes. In our experiments the use of a microprocessor controlled transistor switch with programmable cleaning cycles, allowed us to achieve operation times of up to hours with acceptable bubble quality. Optical feedback based on information from pulsed time lines appears, therefore, as a simple though powerful approach to test more sophisticated control algorithms.

Acknowledgements

This work was supported by the French Agence Nationale de Recherche Projet ANR-11-BS09-018 SepaCoDe. We appreciate valuable stimulating discussions with the SepaCoDe team, in particular Laurent Cordier, Azeddine Kourta and Michel Stanislas.

References

Aström KJ and Murray RM (2010) Feedback systems: an introduction for scientists and engineers. Princeton university press.

Bao F, Dallmann, UC (2004) Some physical aspects of separation bubble on a rounded backward-facing step . *Aerospace Science and Technology* 8: 83–9

Clutter, DW and Smith AMO (1961) Flow visualization by electrolysis of water. *Aerospace Eng.* 20:24-27, 74-76

Gautier N and Aider JL (2013) Control of the separated flow downstream a backward-facing step using real-time visual feedback. *Phil Trans R Soc A* 469

Gautier N and Aider JL (2015) Frequency-lock reactive control of a separated flow enabled by visual sensors. *Exp. Fluids* 56:1–10

Kaiser E, Spohn A, Cordier L and Noack BR (2013) Local forcing of laminar separation bubbles. *Proceedings of the 8th International Symposium On Turbulent and Shear Flow Phenomena (TSFP-8)*

Pastoor M, Henning L, Noack BR., King R and Tadmor G (2008) Feedback shear layer control for bluff body drag reduction. *J. Fluid Mech.* 608: 161-196