Closed-loop Control of Laminar Separation Bubbles

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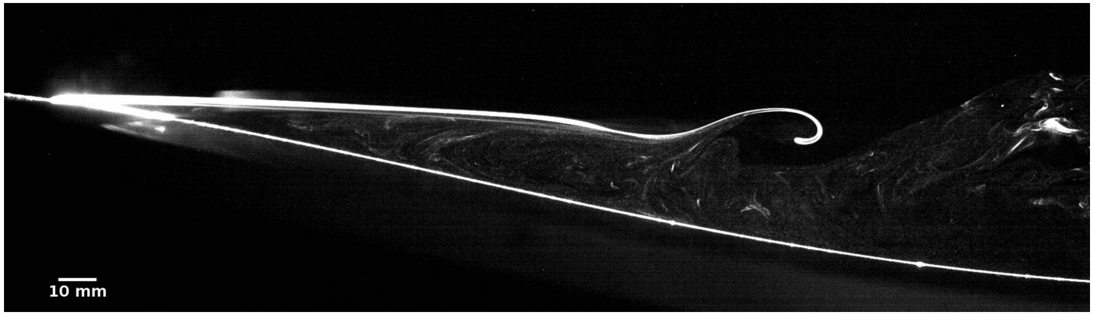
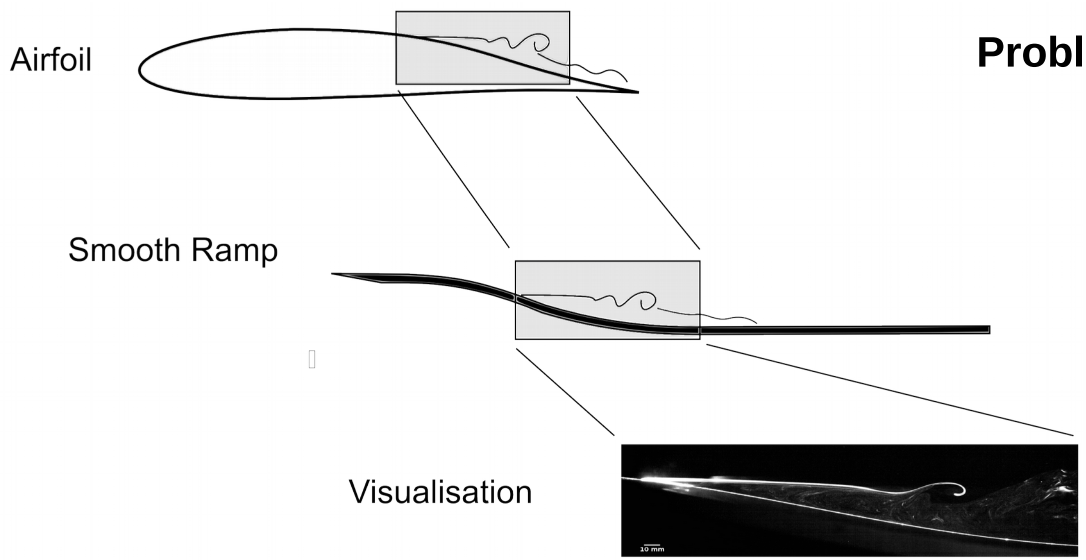


ANR SepaCoDe - Flow separation control

Motivation



Problems:

- Lift reduction
- Drag increase
- Unsteadiness

Goal: Test closed-loop control to minimize impact on global flow

Need :

- Controlled canonical flow conditions
- Low actuation levels for actuation
- Optical sensing of the flow state (real time)

Outline

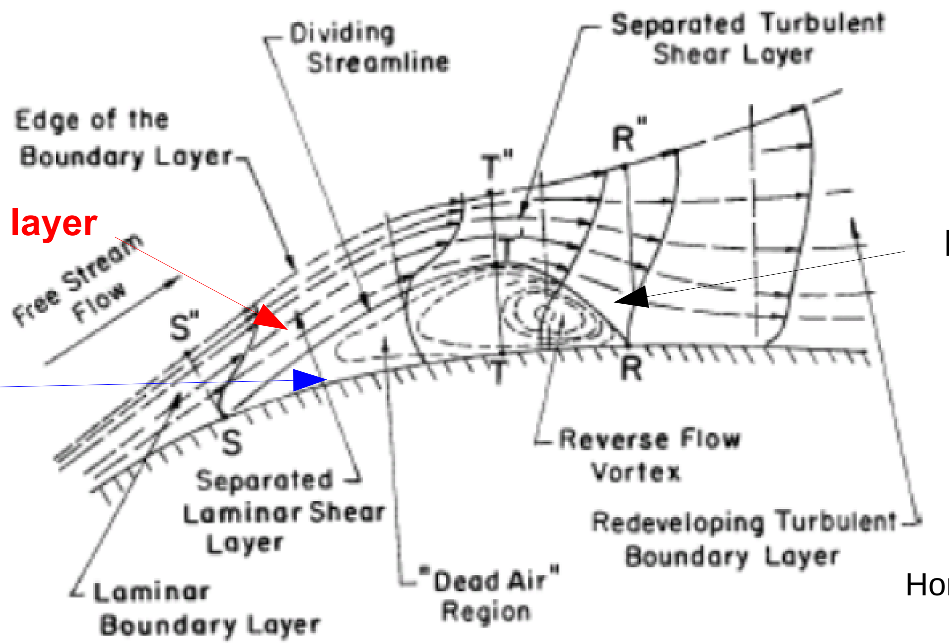
- Summary of L.S.B. properties
- Experimental set-up
- Open-loop periodic forcing
- Closed-loop control
- Conclusion

Main Aspects of L.S.B.

Structure of laminar separation bubbles – or better transitionnal separation bubbles

Convectively unstable shear layer
Kelvin Helmholtz vortices

Low frequency flapping



Bubble bursting

Horten (1968)

Experimental:

Tani (1964)

Gaster (1967)

O'Mera & Mueller (1987)

Watmuff (1999)

Serna & Lázaro (2014)

“

Numerical:

Pauley *et al.* (1990)

Rist & Maucher (1994)

Theofilis (2003)

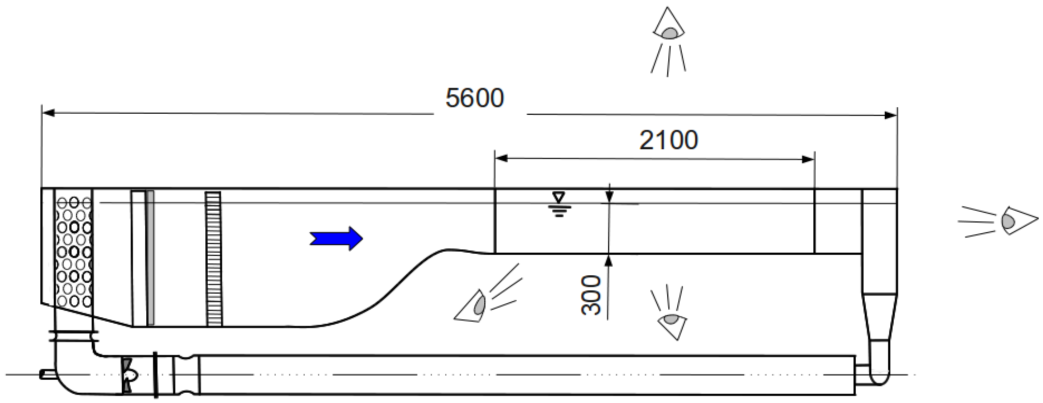
Marxen *et al.* (2009)

Alizard *et al.* (2009)

“

And many others !

Water Tunnel Facility



Specifications:

- flow section 0.3 m x 0.50 m x 2.10 m
- speed < 0,50 m/sec
- maximal power 5 kW

Experimental techniques:

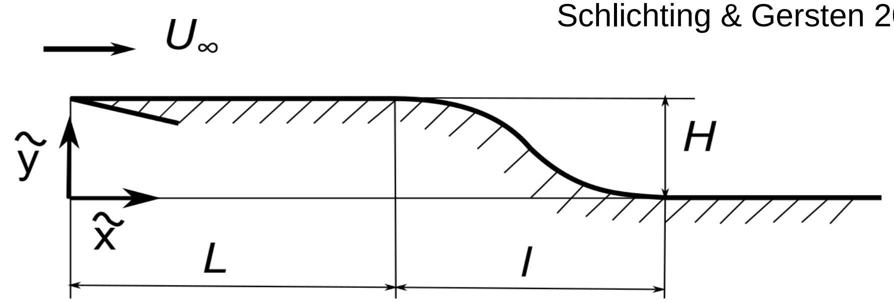
- hydrogen bubbles (Schraub et al. 1965)
- electrolytic precipitation (Taneda et al. 1975)
- dye
- PIV (2D-2C)

Smooth Ramp Configuration

Ramp parameters

Sommer 1992 (triple deck)

Schlichting & Gersten 2006



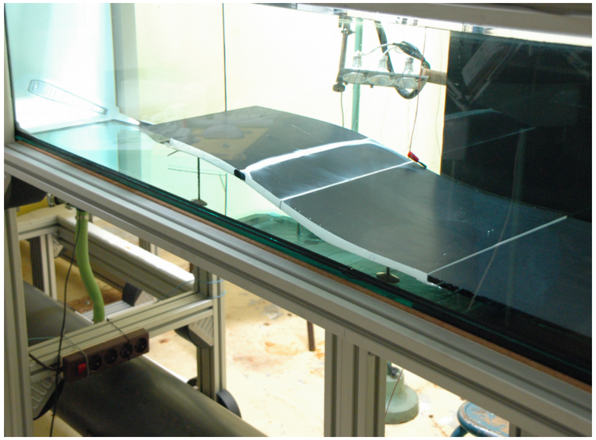
$$\mathrm{Re} = \frac{U_\infty L}{\nu}, \quad \frac{l}{L}, \quad \frac{l}{H}$$

+

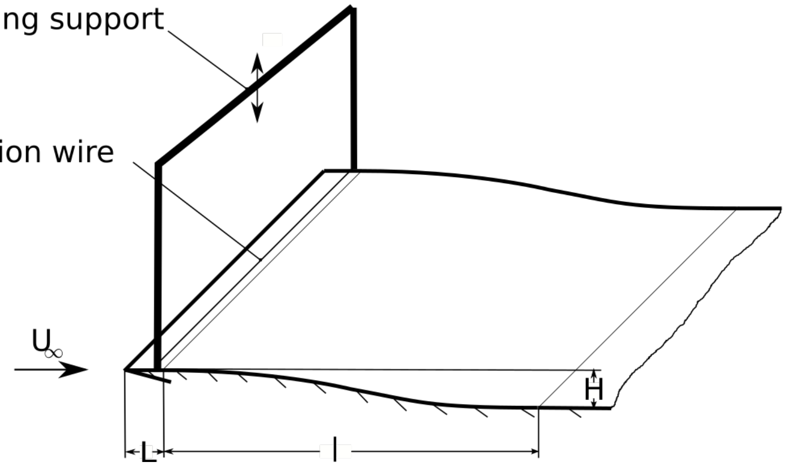
$$1 \le \tilde{x} \le 1 + l: \qquad f(\tilde{x}) = \left[20\left(\frac{\tilde{x}}{l}\right)^7 - 70\left(\frac{\tilde{x}}{l}\right)^6 + 84\left(\frac{\tilde{x}}{l}\right)^5 - 35\left(\frac{\tilde{x}}{l}\right)^4 + 1\right]$$

Range: $3 \cdot 10^3 \le \mathrm{Re} \le 3 \cdot 10^4$ $\quad \frac{l}{L} = 6$ $\quad \frac{l}{H} = 10$

Ramp installed in water tunnel



Actuator system

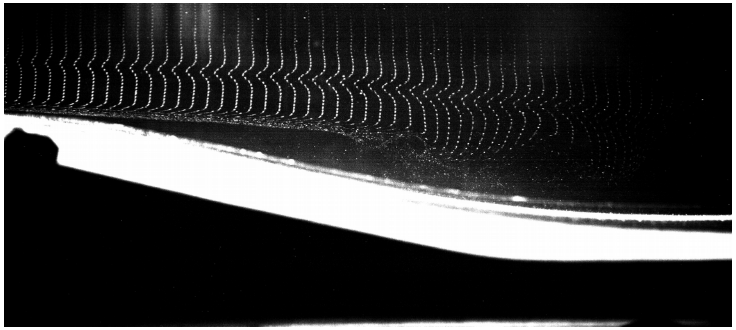


Actuator

- Dimensions: $\varnothing = 0.13\,mm \approx \frac{1}{100}\delta$
- Excitation frequency: $0.16 \leq f_e / f_n \leq 5$
- Maximal Amplitude: $a_{max} \simeq 40\,\%\,\delta$

Inside B.L. $\mathrm{Re}_{wire} \simeq 5 - 10$

Test : perturbation outside B. L.

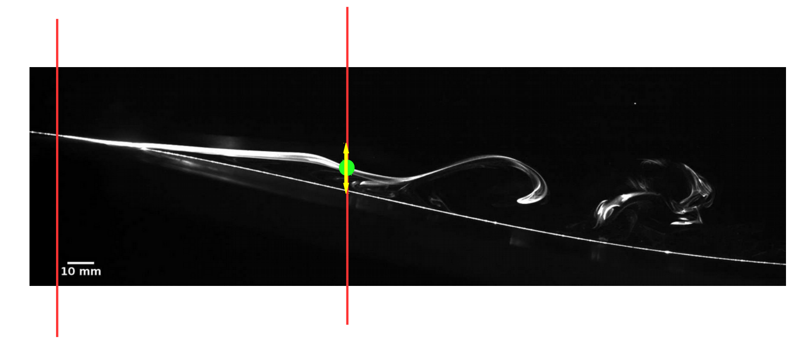


Effect of Open-loop Actuation

Optical measurement of the growth rate

Lasheras & Choi (1988), Julien *et al. (2003)*

Instantaneous streakline

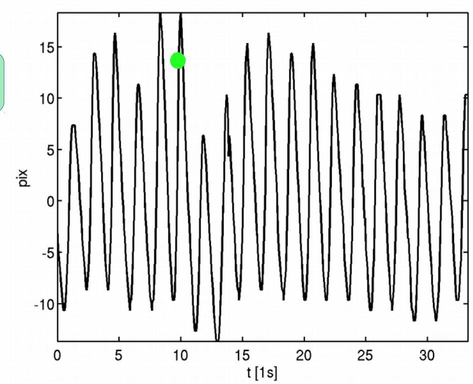


Kaiser *et al.* (2013)

Electrolytic precipitation , Tanji (1975)

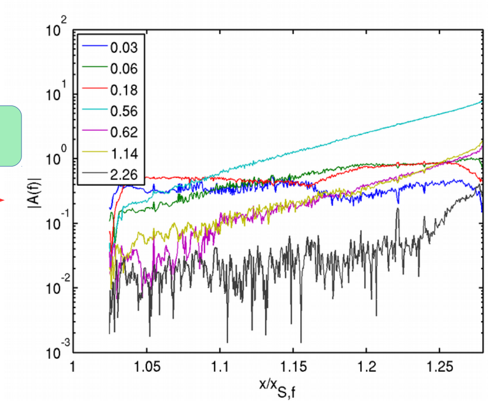
Time evolution of amplitude for one given x'

Image processing



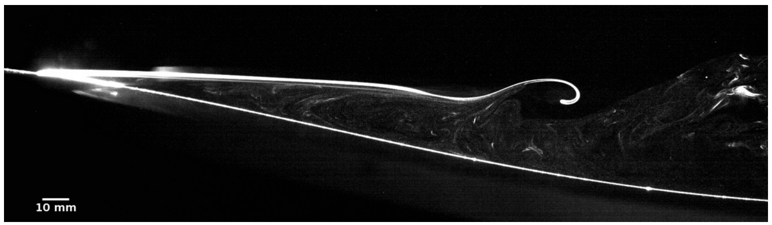
FFT

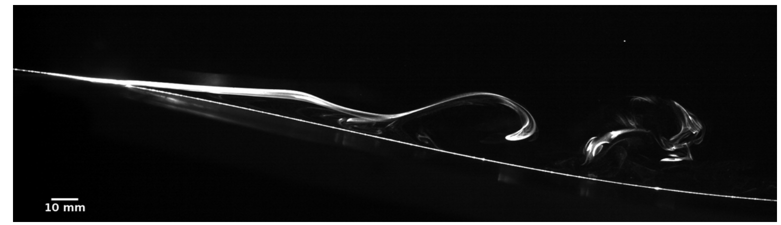
Spatial evolution of modes



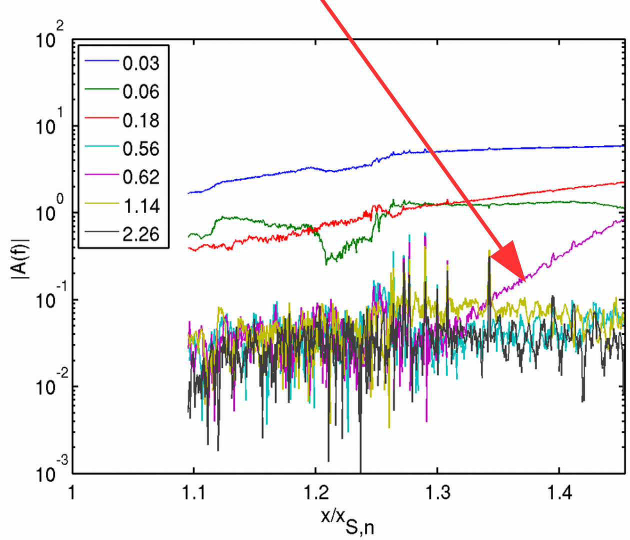
Identification of Most Unstable Modes

Re = 7700 **Natural flow** | **Excited flow ($f_e = 0.9 f_n$)**

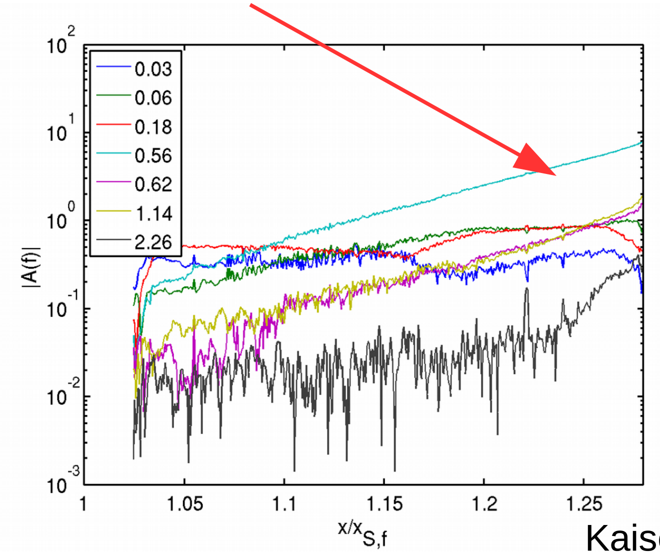




Natural K.H. mode



Excited mode



Kaiser *et al.* (2013)

- Most unstable mode with *St* = 0.034 (PIV) - theory Ho & Huerre (1984) *St* = 0.032

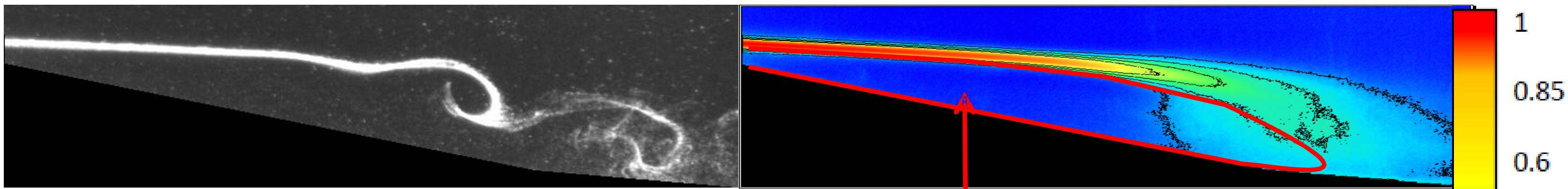
Open-loop Forcing – Objective Function

Natural flow :

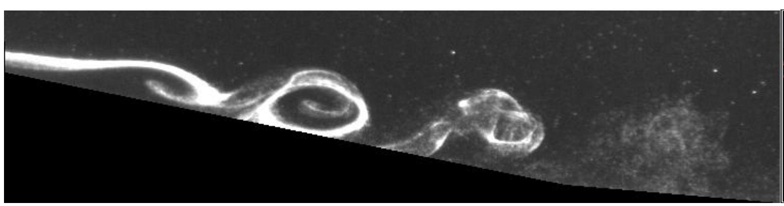
Re=7900

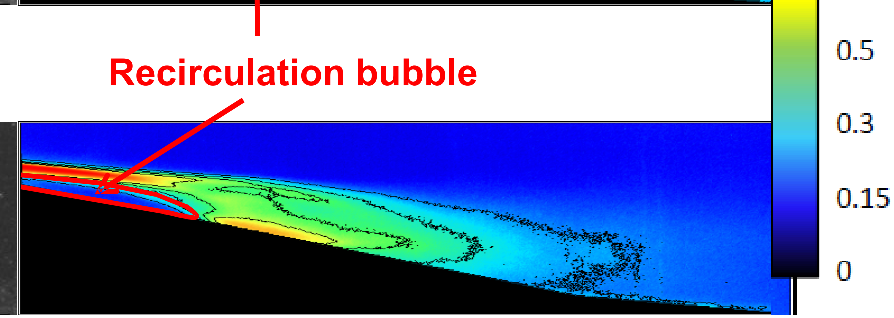
Greyscale (8-bit) image

Normalized light intensity: I = 0 to 1



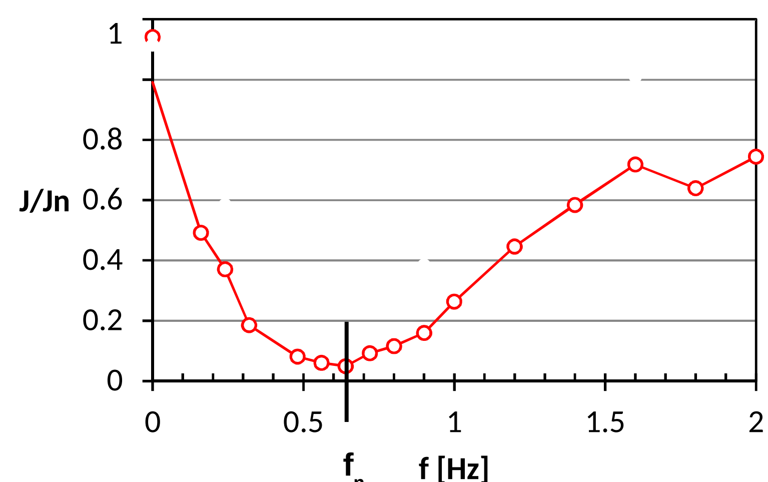
Best actuation frequency f /f_n=1 :





Continuous production of H_2 bubbles

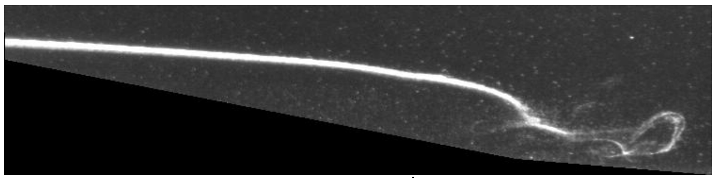
Open-loop mapping



- Evaluated a posteriori from mean images
- Use of threshold for light intensity (I=0.4)

Optical Feedback Control – Global Sensing (PCA)

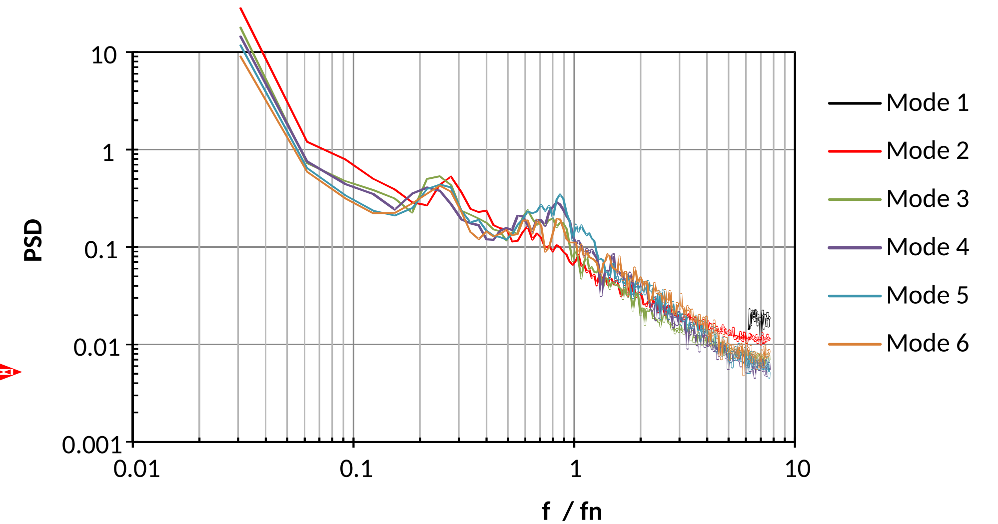
Hydrogen bubbles - continuous production



$$M\,[m\times n] = U\Sigma V^{*}$$

$$S_{1\ldots n}(t)$$

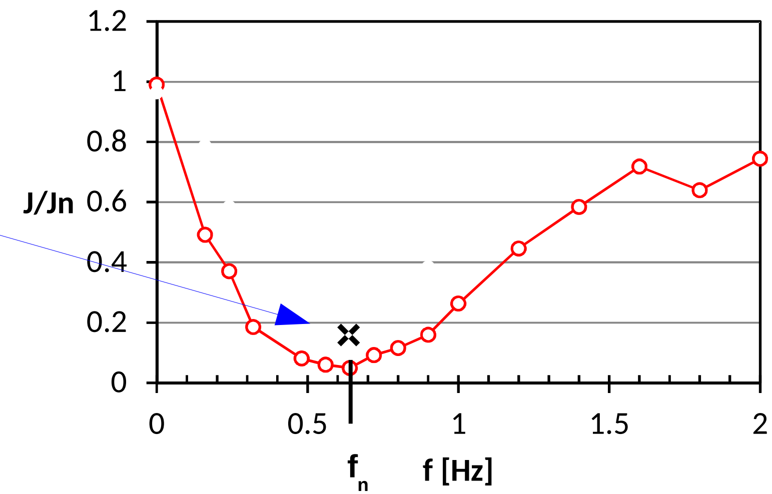
Spectra of the time series of 6 most energetic modes



Feedback a selected eigenvalue!

$$b(t) = f(S_n)$$

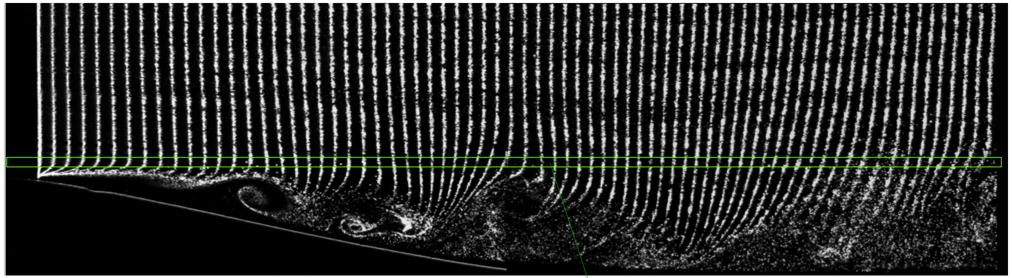
Mode 4 produces actuation at the natural frequency



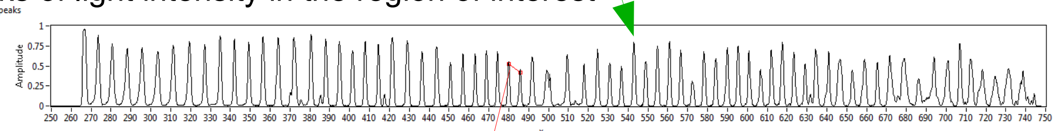
Velocity Measurements with Hydrogen Bubbles

Measurement of velocity along a horizontal line

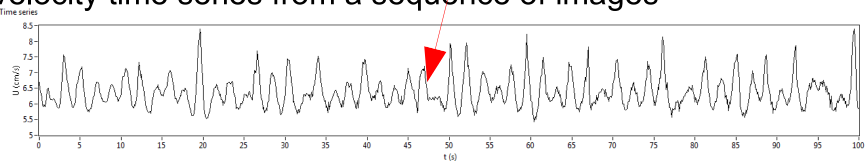
1. Instantanious visualisation



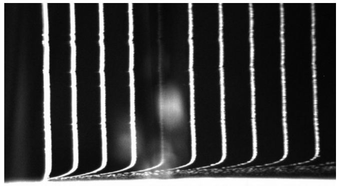
2. Peaks of light intensity in the region of interest

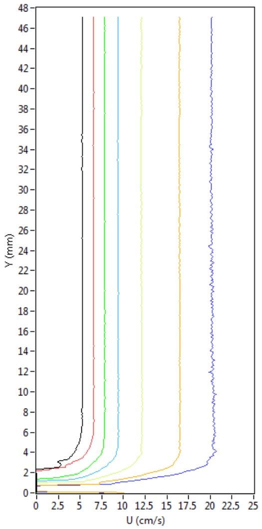


3. Local velocity time series from a sequence of images

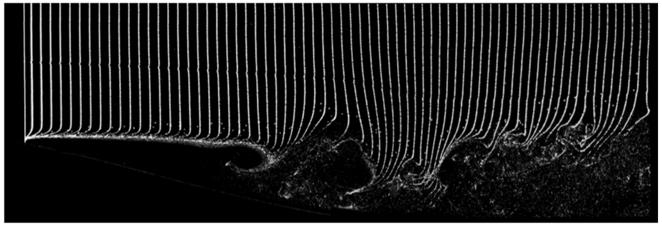


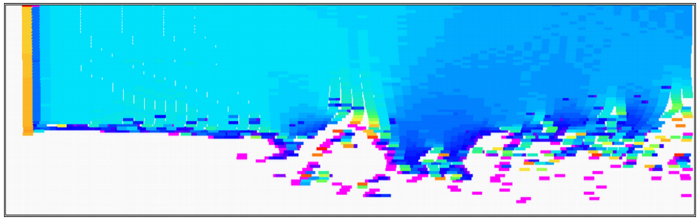
Velocity Profiles inside B.L. (3000 ≤ Re ≤ 20000)





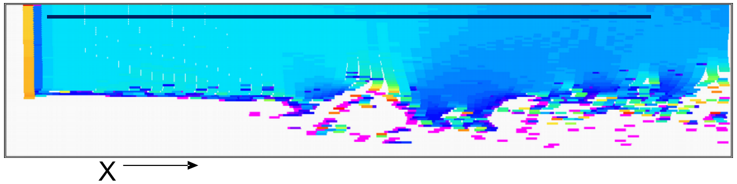
Velocity Field of U component (Re = 7900)





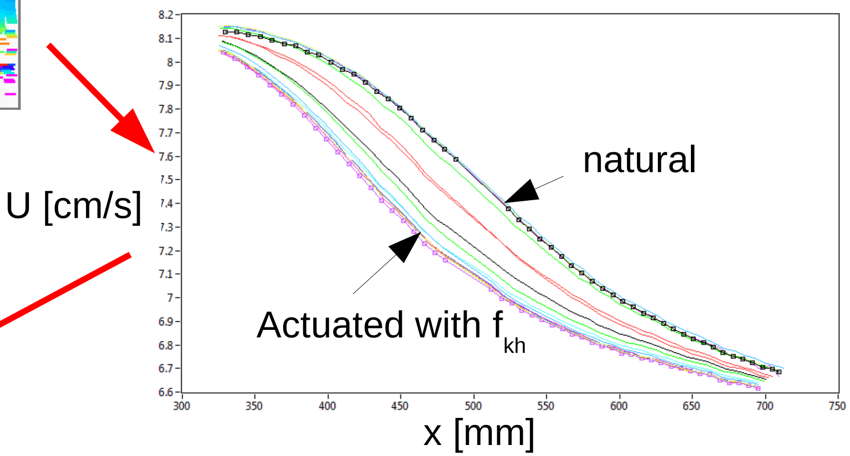
Objective Function using Velocity Measurements

Extract instantaneous velocity u along a line:



Re=7900

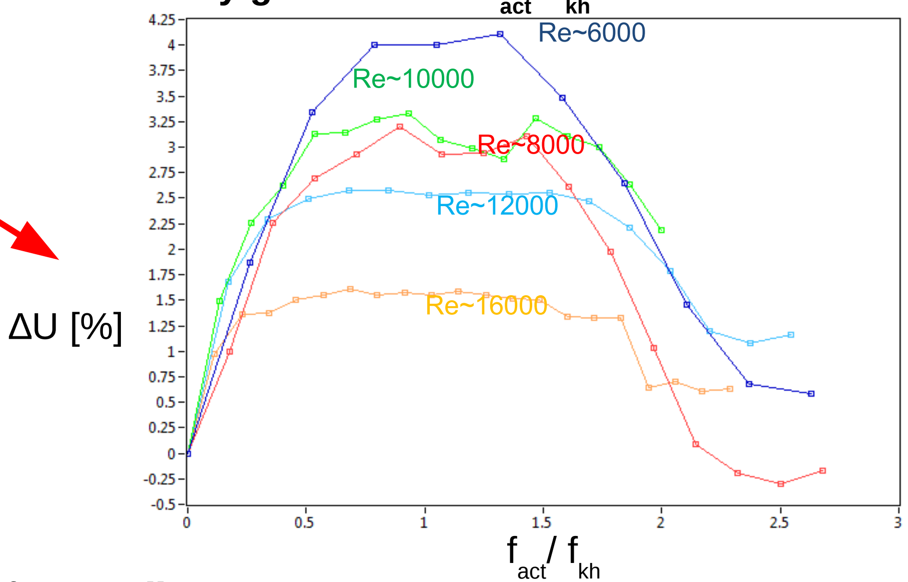
Mean velocity U vs. x



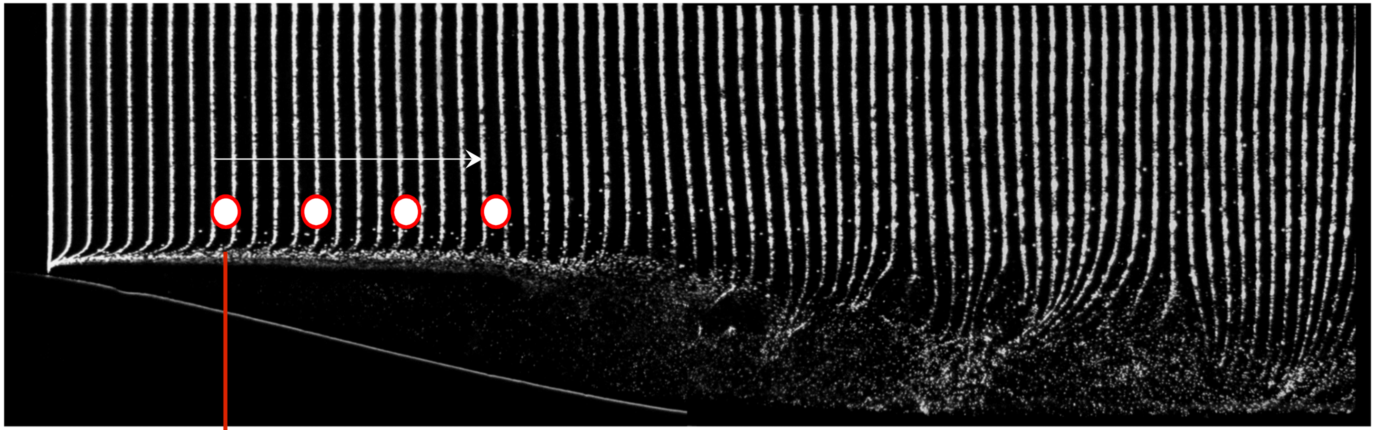
Instantaneous objective function

$$J = \int_{x_1}^{x_2} \left(U_{nat}(x) - U_{act}(x) \right) dx$$

Velocity gain in % vs. f_{act} / f_{kh}



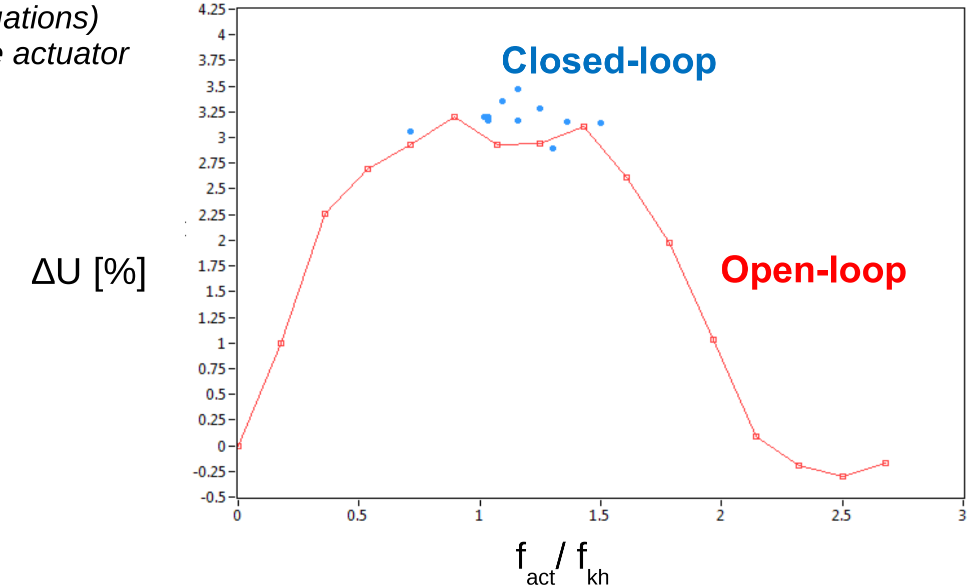
Closed-loop Control - Local Sensing



Re = 7900

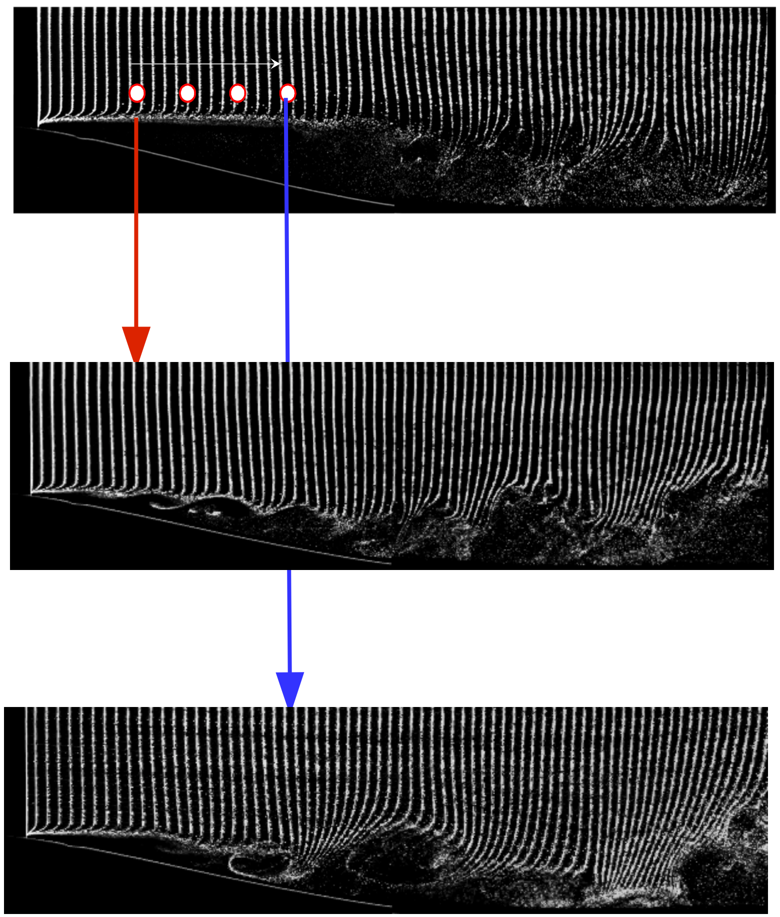
$$b = A \times s(t) + C$$

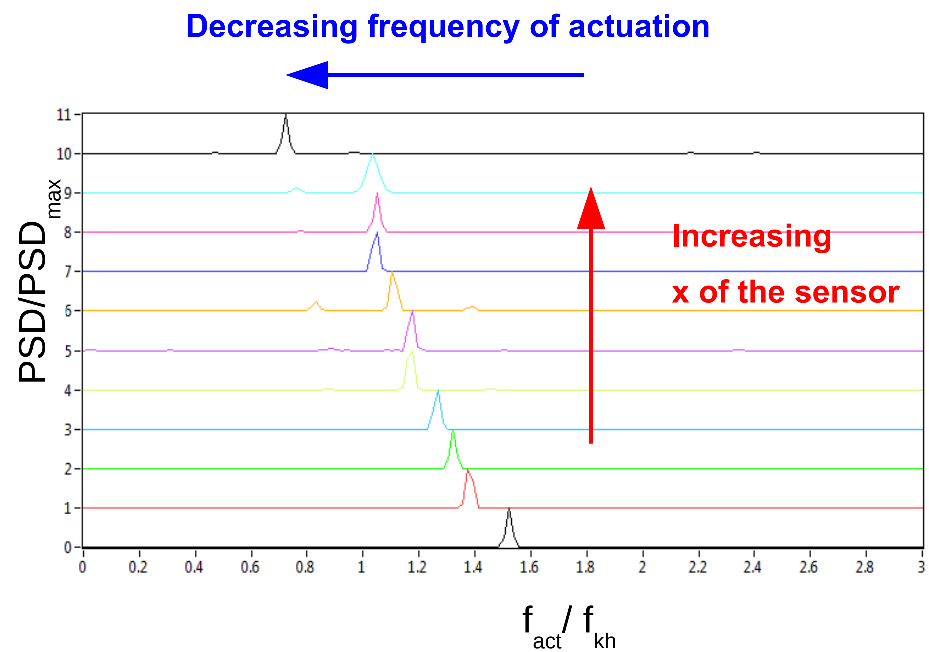
b - actuator displacement
s - sensor signal (velocity fluctuations)
C – offset (mean position of the actuator above the ramp)



Closed-loop Control - Position of Sensor

Re = 7900





Actuation frequency depends on sensor location !

Conclusion

- **Actuation around the natural KH frequency proves to be most efficient.**
- **The definition of a cost function appears to challenging.**
- **Local sensing leads to frequency selection for actuation.**
- **Closed-loop control in combination with convective transport of perturbations leads to periodic forcing.**
  - Similar to control of mixing layer see V.Parezanović *et al.* (2016) .
- **Lagrangian velocity measurements are promising for long experimental runs in combination with real-time measurements.**