MEC651
Instabilities and control of shear flows

Objectives

The objective of the course is to introduce and adapt modern flow control techniques in order to stabilize flow instabilities and therefore delay transition to turbulence. Both open-loop and closed-loop control strategies will be presented. These issues play a crucial role in both aeronautical and mechanical engineering applications.

Also:

- acquire new methods, algorithms
- numerical practice
- physics involved

How?

1/3: Theory

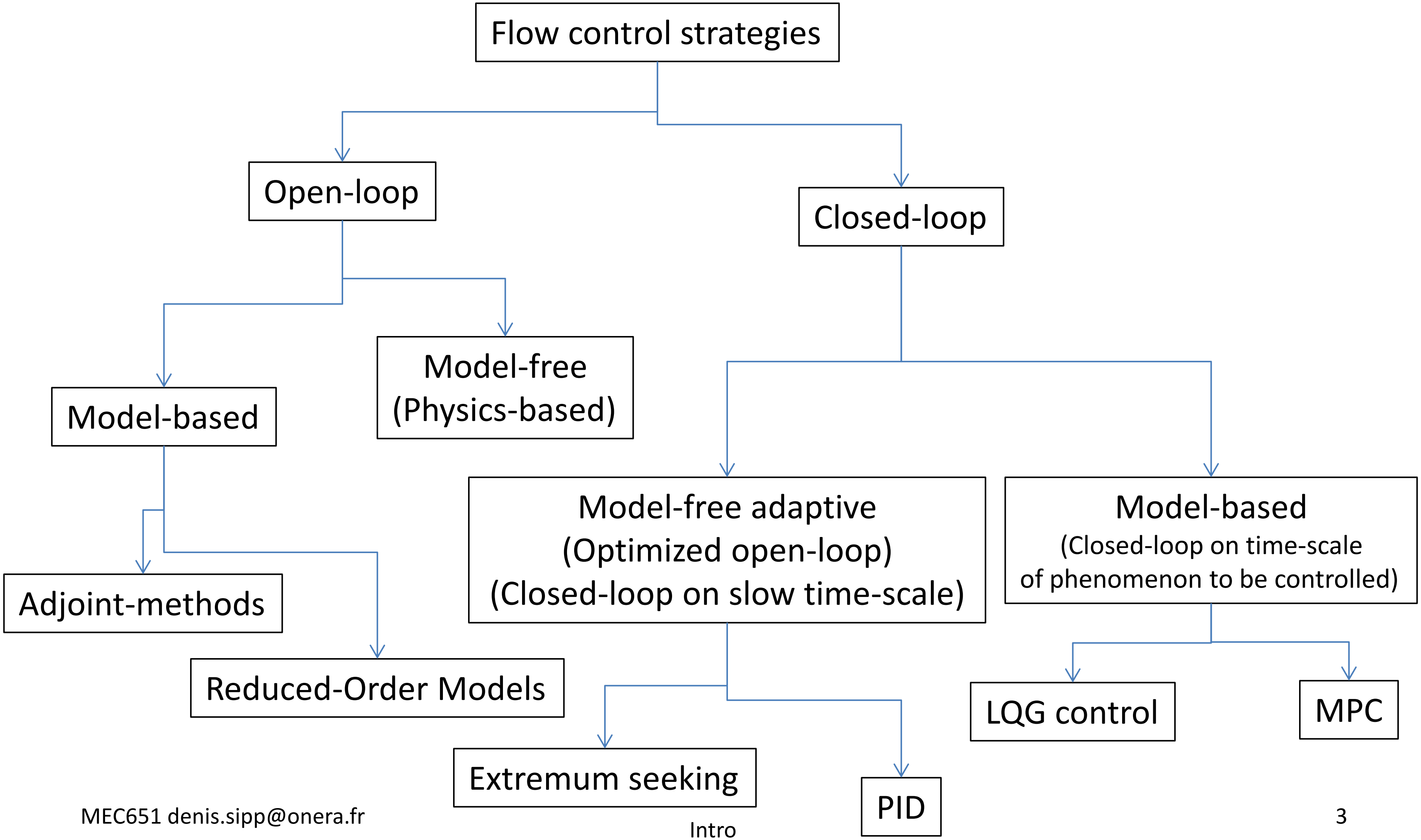
1/3: Mathematical practice

1/3: Numerical practice (codes based on FreeFem++ and Matlab/Octave)

Motivations

- Wide range of applications
  - suppression of instabilities
  - exploration of previously inaccessible parameter regimes
  - increase of stability margins
  - diminish sensitivities to external noise sources
  - improve performance (decrease drag)
  - minimize environmental impact
  - Aerodynamics/combustion/aeroacoustics/fluid-structure/…
- Design of flow control devices for manipulating inherent flow behaviour

Different types of flow control



Instabilities

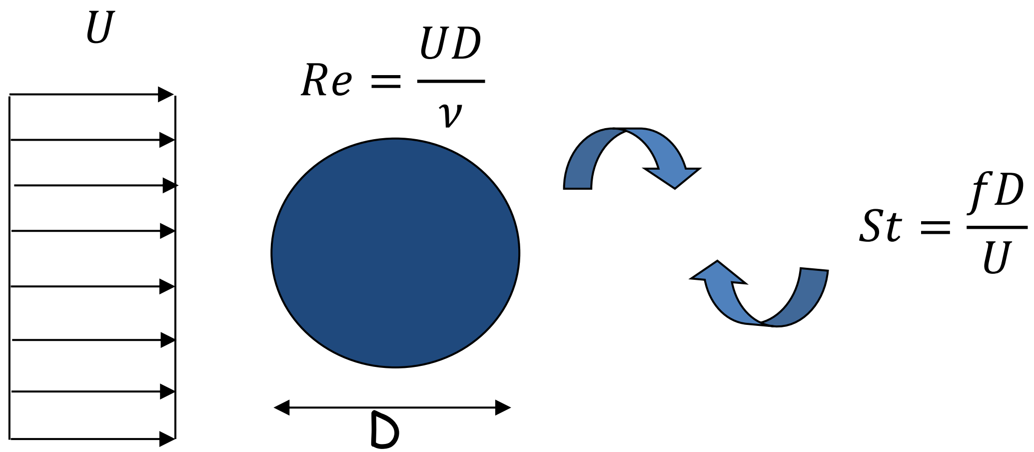
Oscillator flows

- Frequency spectrum characterized by peaks
- Absolutely unstable flows
- Not sensitive to environmental noise

Amplifier flows:

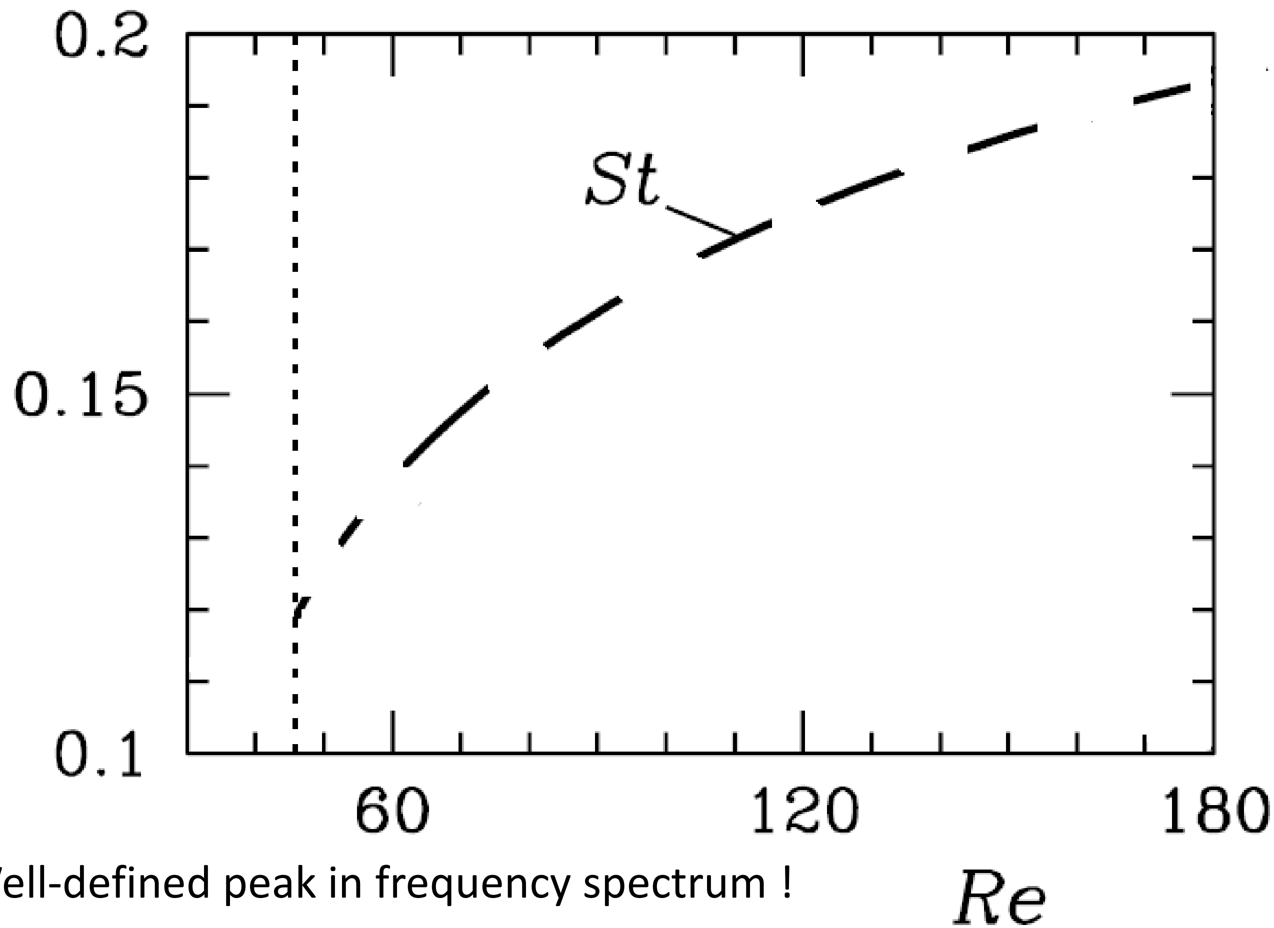
- Broadband spectrum
- Convectively unstable
- Dynamics reflects upstream noise
- Boundary layer flow, jets, shear-layers without counter-flow, wake vortices

Cylinder flow



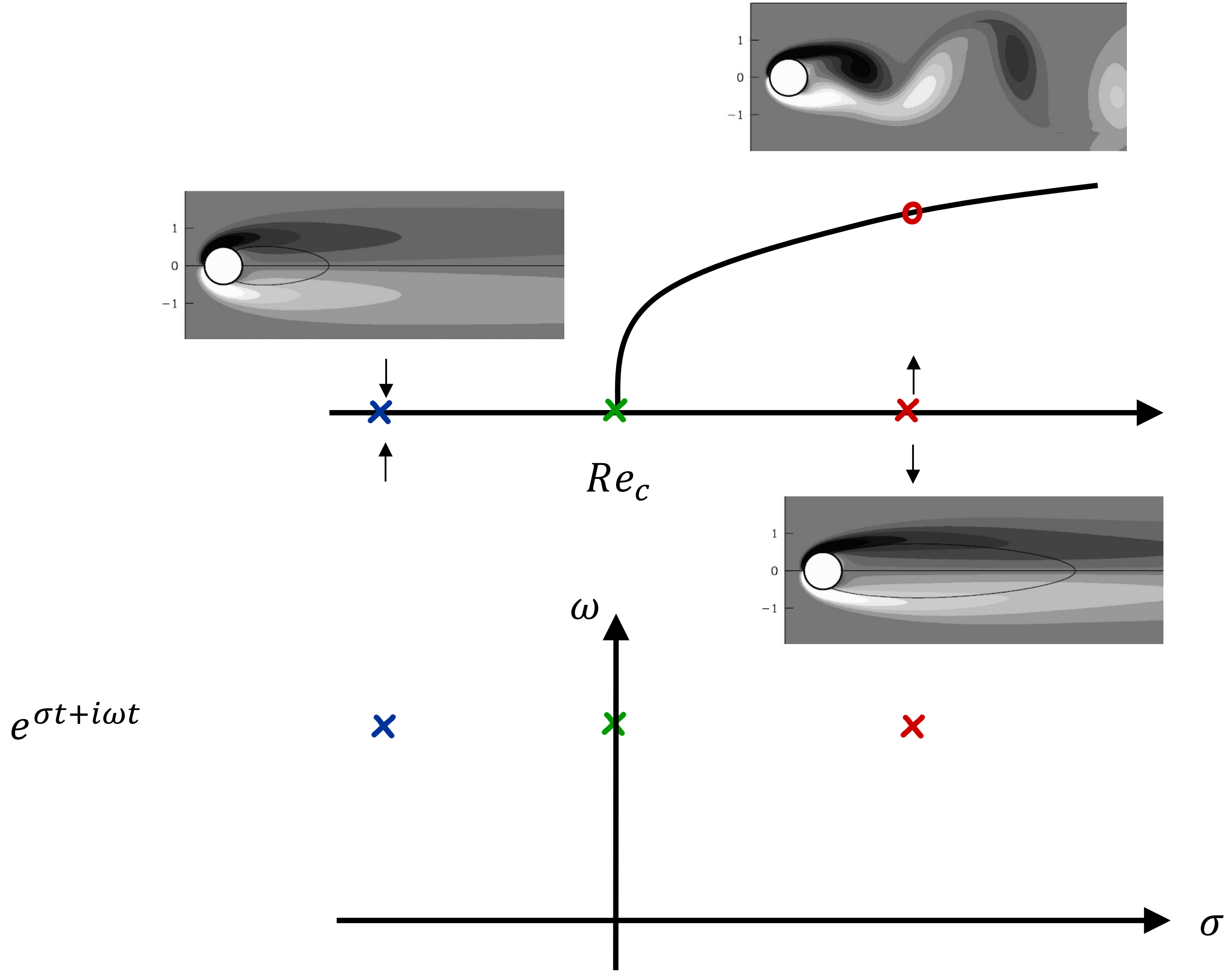
$RE > 47$: appearance of unsteadiness

Cylinder flow



Well-defined peak in frequency spectrum !

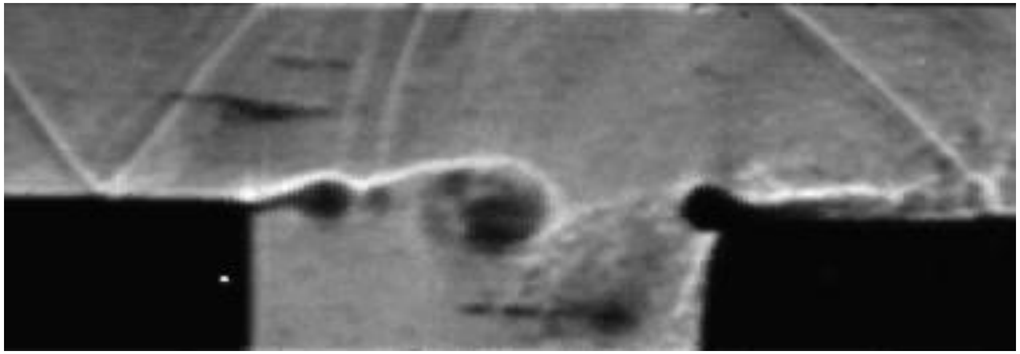
Oscillator flows / bifurcation



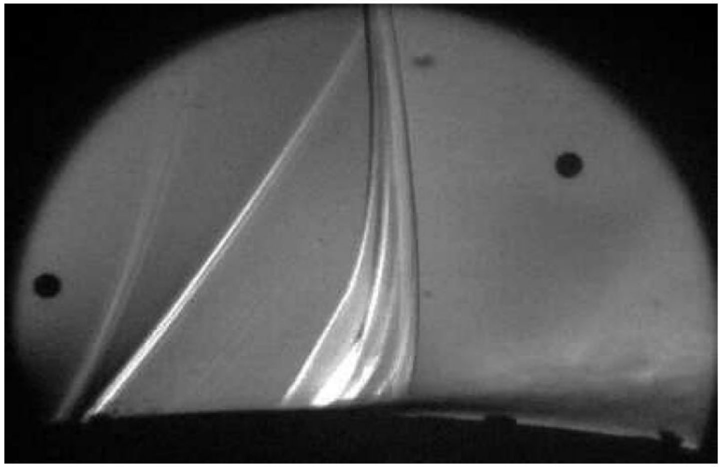
video-dns.mpeg

Other oscillator flows (high Re number flows)

Cavity flow

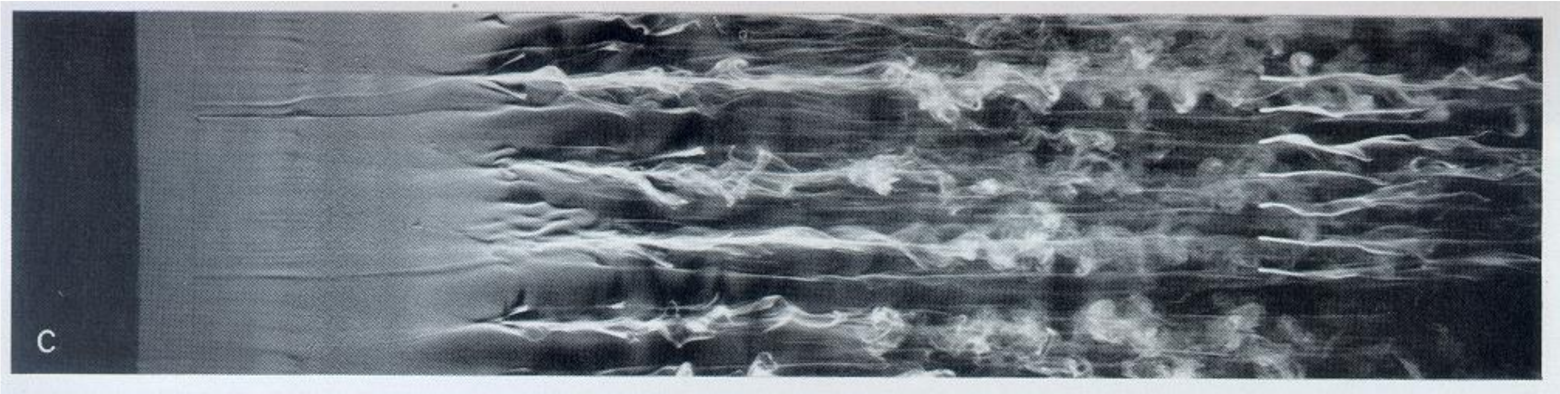


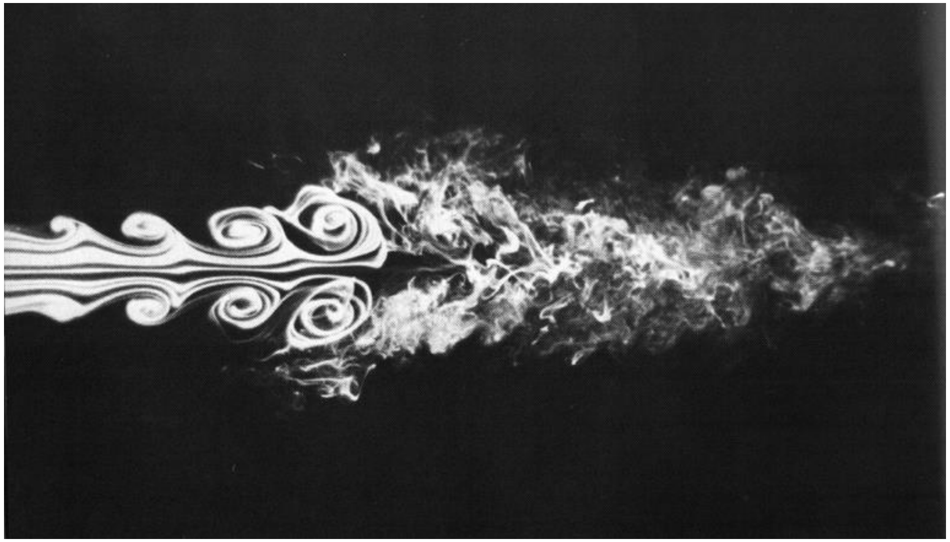
Buffet over aerofoils

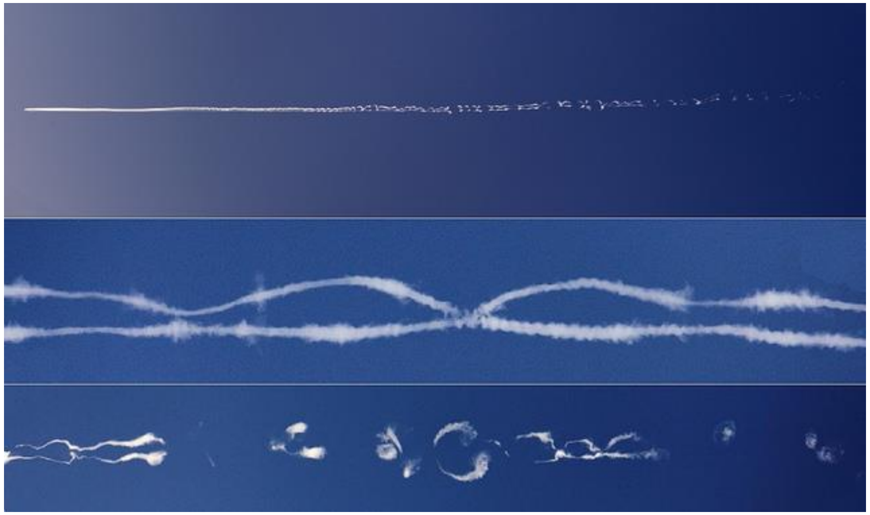


Other : buffet over airfoils, light jets, screeching jets, shear-layers with strong counter-flow

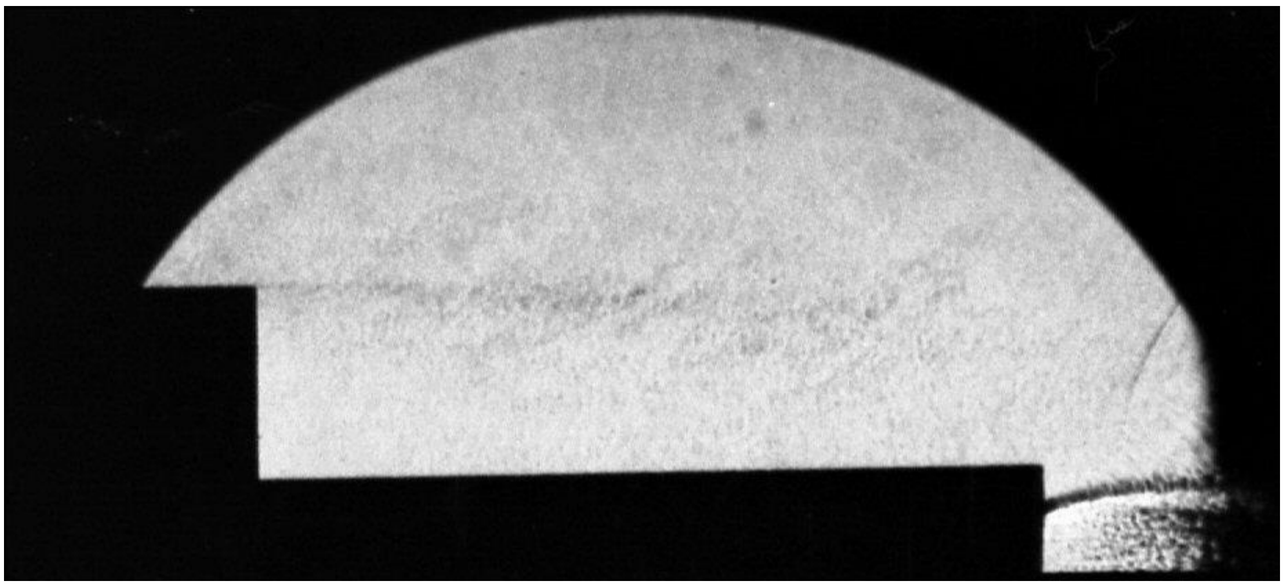
Amplifier flows





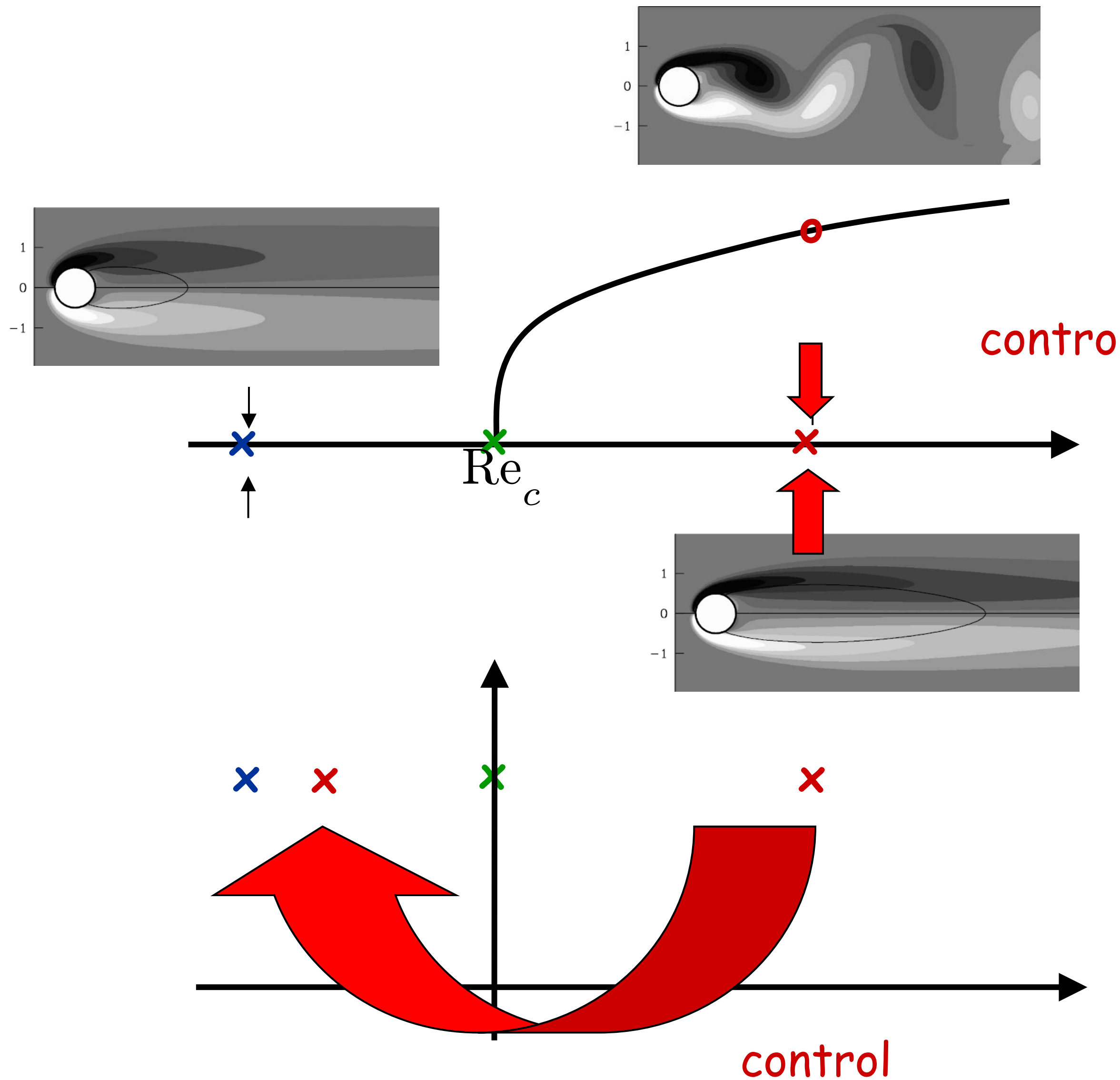


Oscillator / Amplifier flows

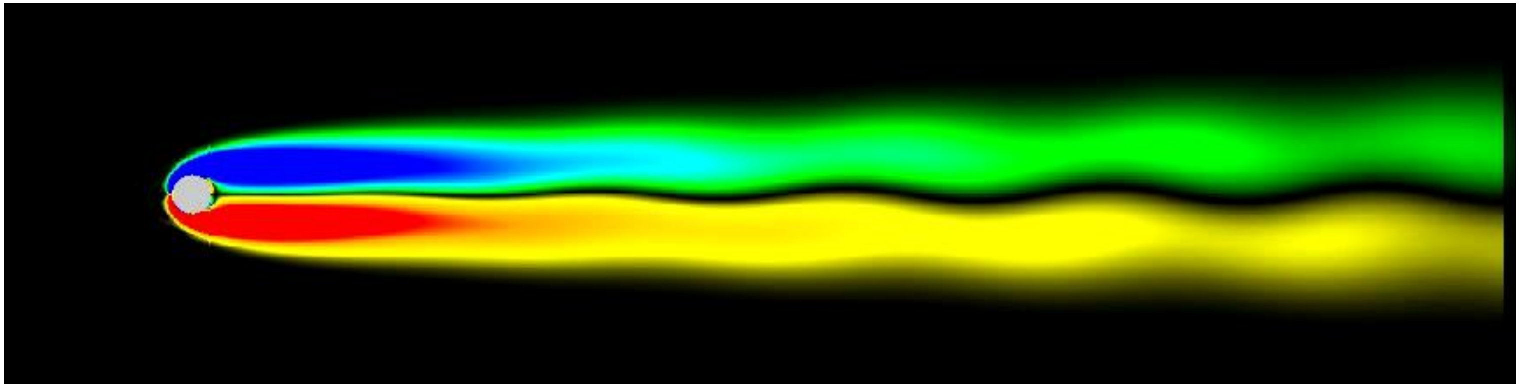


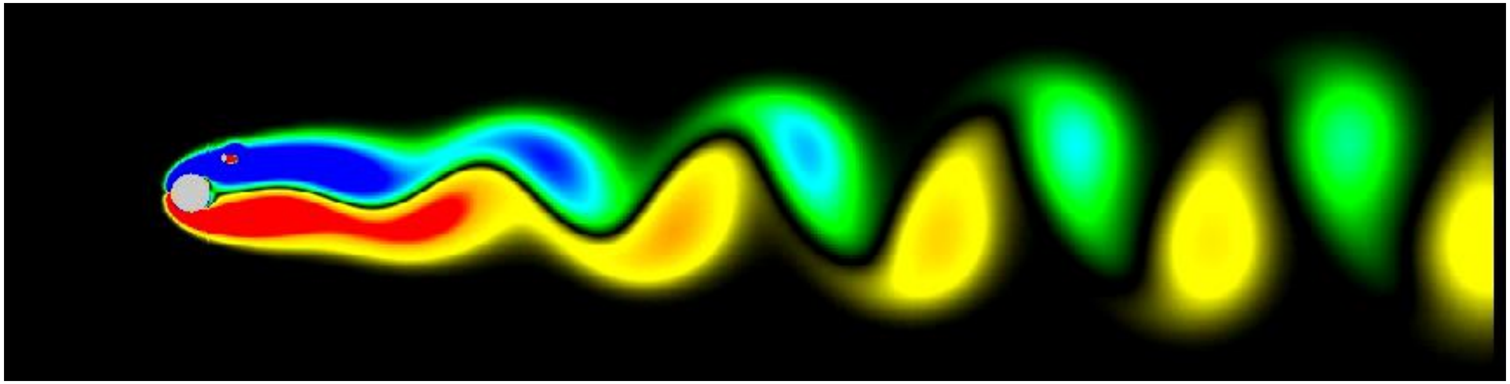
Ariane V after-body, ONERA

Control of oscillator flows

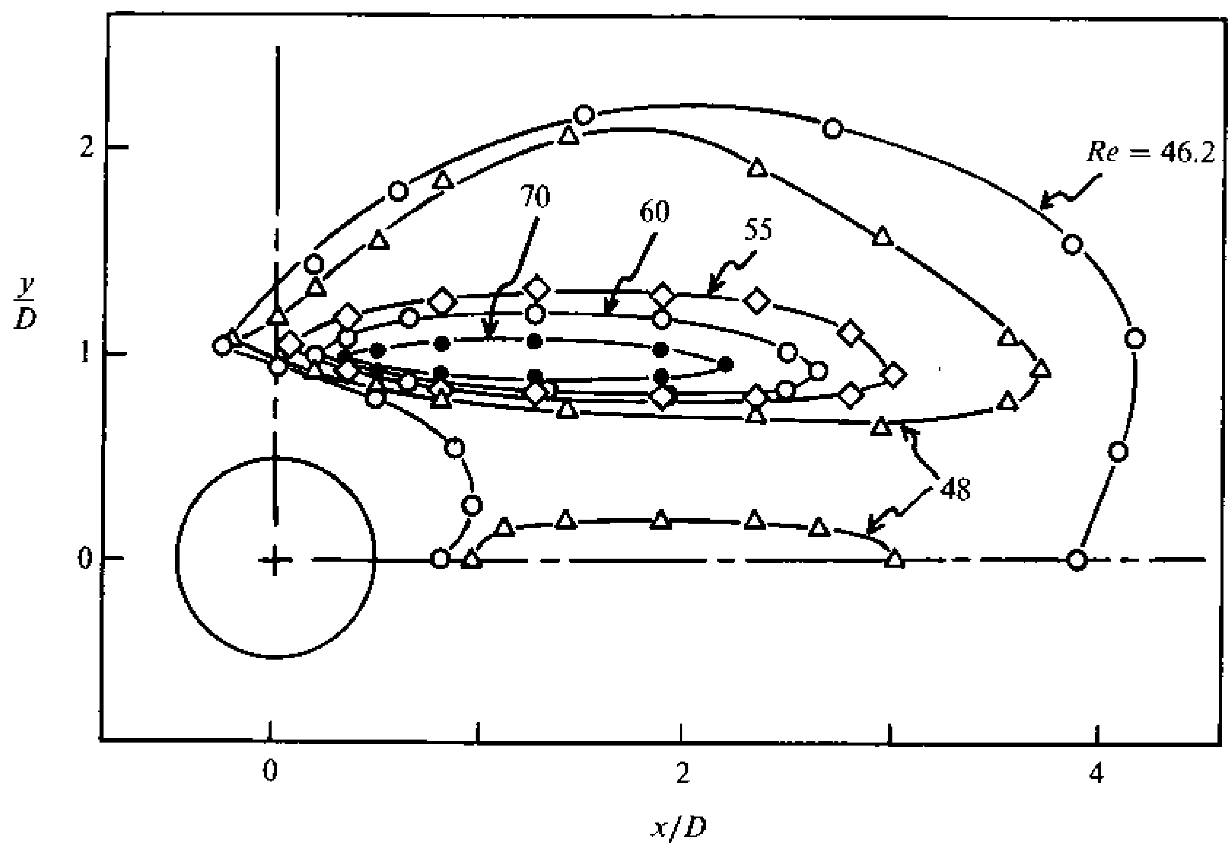


Open-loop control with cylinder



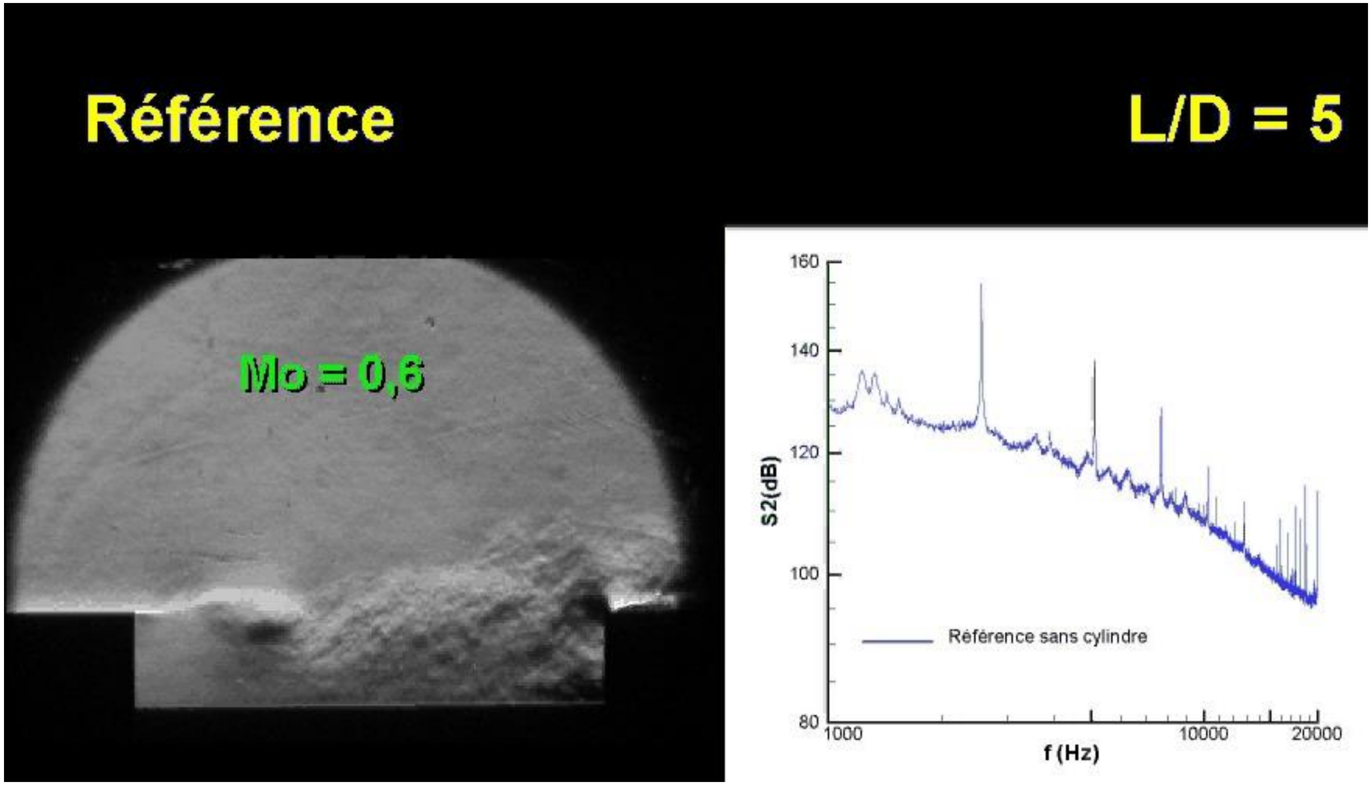


Open-loop control with cylinder



Strykowski & Sreenivasan JFM 1990

Open-loop control with cylinder



Open-loop control with symmetry-breaking forcing

Harmonic forcing with synthetic jets

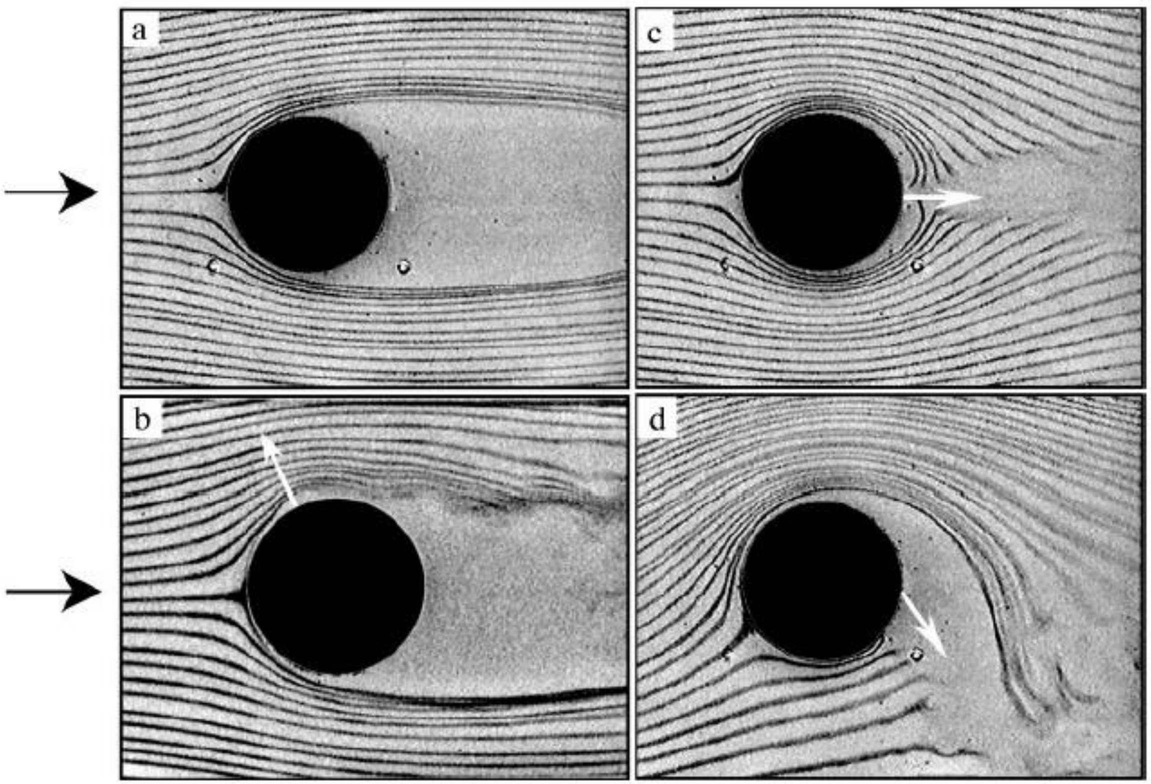


Figure 7 Smoke of the flow around a circular cylinder visualization: (*a*) baseline; and (*b*) actuated: $\phi = 0$, $\gamma = 60°$ and (*c*) 180°, and (*d*) $\phi = 120°$, $\gamma = 180°$.

Glezer et al. ARFM 2002

Open-loop control with symmetry-breaking forcing

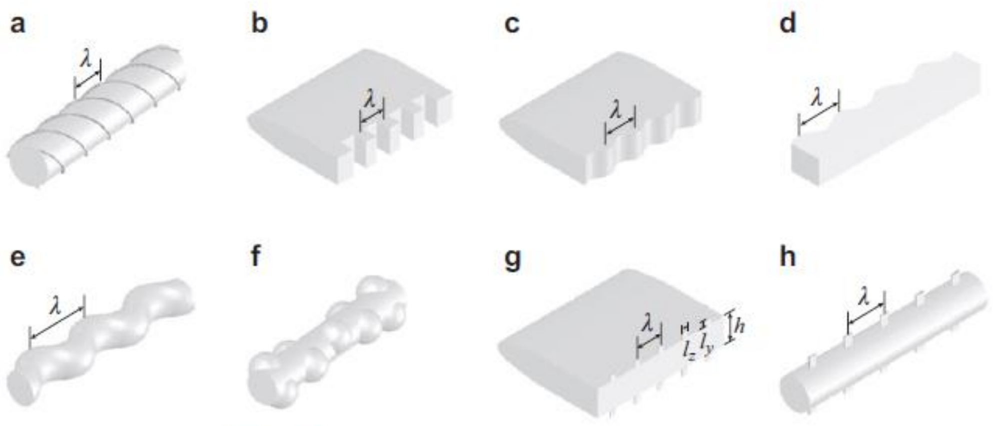


Figure 4
3D forcing by passive means: (*a*) helical strake, (*b*) segmented trailing edge, (*c*) wavy trailing edge, (*d*) wavy stagnation face, (*e*) sinusoidal axis, (*f*) hemispherical bump, and (*g*, *h*) small-size tab.

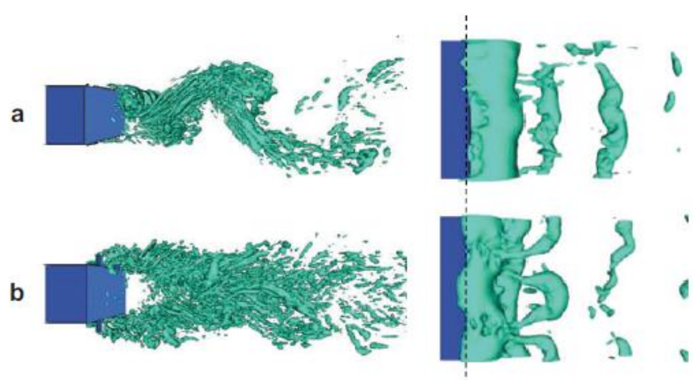


Figure 5
Instantaneous vortical structures in a wake ($Re = u_\infty h/\nu = 4200$): (*a*) uncontrolled flow and (*b*) controlled flow with tabs of $(\lambda/h, l_y/h, l_z/h) = (2, 0.2, 0.2)$. Shown are the 3D views of vortical structures (*left column*) and top views of isopressure surfaces (*right column*). Figure taken from Park et al. 2006.

Choi ARFM 2008

Open-loop control with symmetry-breaking forcing

Wavy spanwise blowing/suction

Choi ARFM 2008

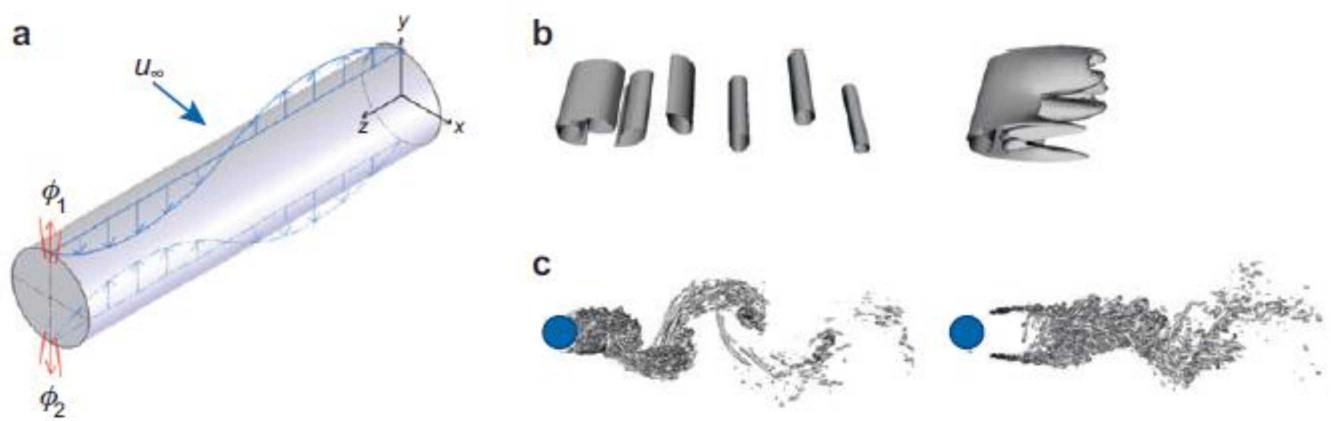


Figure 6

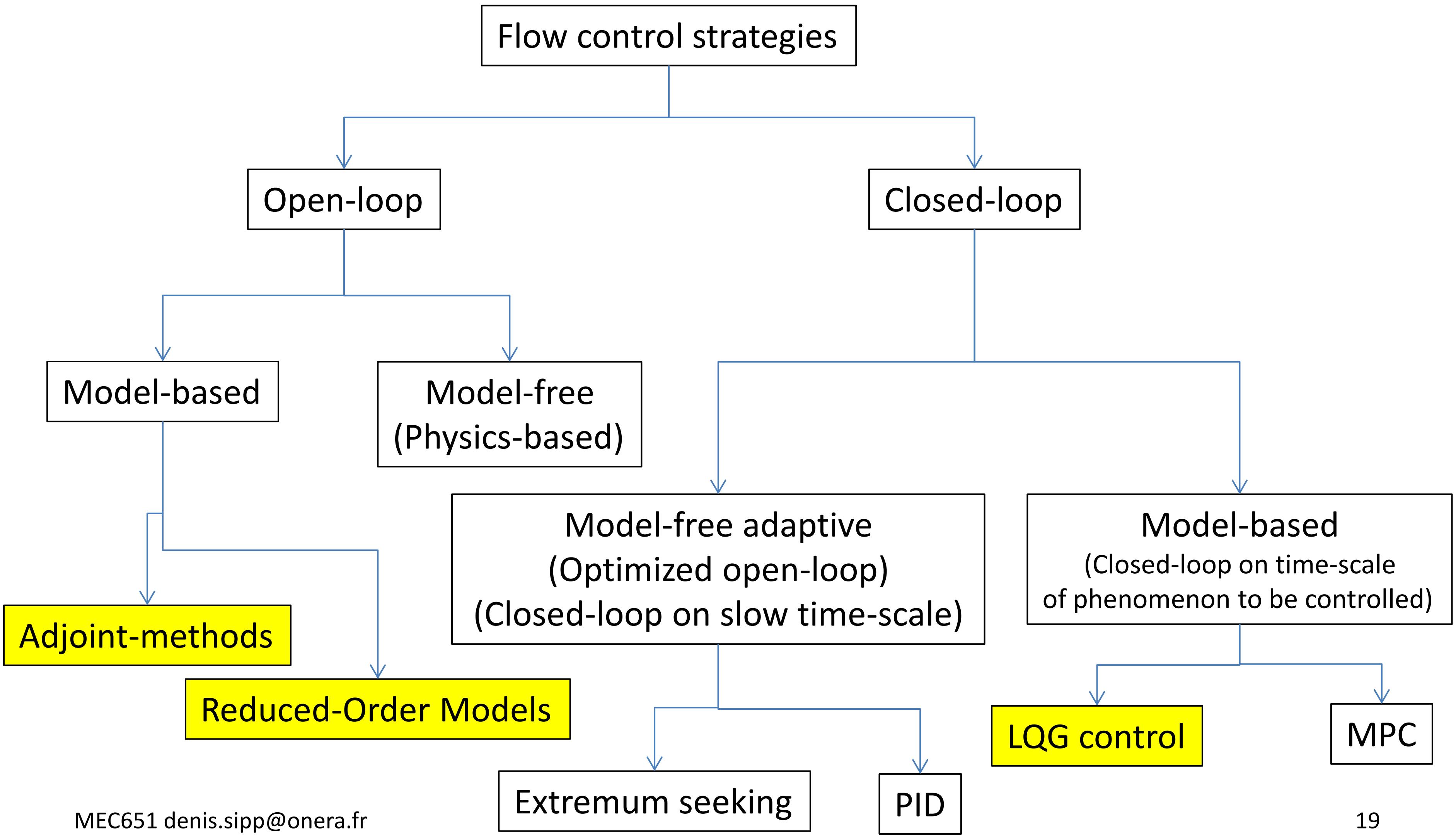
Distributed forcing: (*a*) schematic of the forcing, (*b*) $Re = 100$ ($\lambda = 5d$), and (*c*) $Re = 3900$ ($\lambda = \pi d$). Shown in panels *b* and *c* are the instantaneous vortical structures without (*left column*) and with (*right column*) control. Figure taken from Kim & Choi 2005.

Model-based closed-loop control with estimator/controller

Estimation problem: estim.mp4

Control problem: control.mp4

Outline of course



Outline of course

0/ Instabilities and global modes in open shear-flows.

1/ Open-loop control with adjoint methods: variational formulation, adjoint operators, adjoint global modes, eigenvalue sensitivity.

2/ Open-loop control with amplitude equations: the forced Van der Pol oscillator, multiple time-scale analysis, compatibility condition, bifurcation analysis in real systems.

3/ Model reduction with balanced truncation: input/output dynamics, observability and controllability Gramians, Hankel singular-values, balanced basis.

4/ Closed-loop control with estimator / controller setup: Riccati-based feedback control , full-state information control, partial state information control, estimation and Kalman filtering.

All concepts will be illustrated on cylinder and open-cavity flows.