Flow Control

Jean-Pierre Richard

http://chercheurs.lille.inria.fr/~jrichard/

joint work with

Maxime Feingesicht (Department of Aerospace Engineering, The University of Michigan)

Andrey Polyakov (Inria, centre de recherche Lille - Nord Europe)

Franck Kerhervé (Univ. de Poitiers et CNRS Institut Pprime)

Flow Control

Nonlinear active control of turbulent separated flows: theory and experiments.

Maxime FEINGESICHT

centralelille

Région Hauts-de-France

Lille, France - December 11, 2017

Supervisor: Jean-Pierre RICHARD
Co-supervisors: Andrey POLYAKOV, Franck KERHERVE

Inria INVENTEURS DU MONDE NUMÉRIQUE | CRIStAL Centre de Recherche en Informatique, Signal et Automatique de Lille | INSTITUT P' | Laboratoire Mécanique Lille

https://tel.archives-ouvertes.fr/tel-01801155

This thesis was also achieved in the following framework:

Transports Terrestres Mobilité FR CNRS n° 3733

ELSAT2020 (more specifically project CONTRATECH of the OS4)

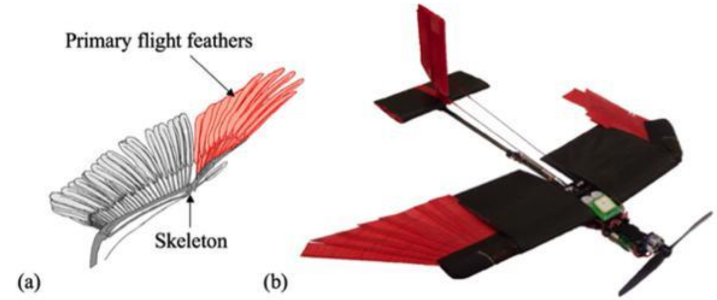
gdr macs

GDR 2502

andrey.polyakov@inria.fr

jean-pierre.richard@inria.fr

… what we won’t make here ☹



… what we won’t make here, either ☹

what we'll only discuss about…

Flow Control

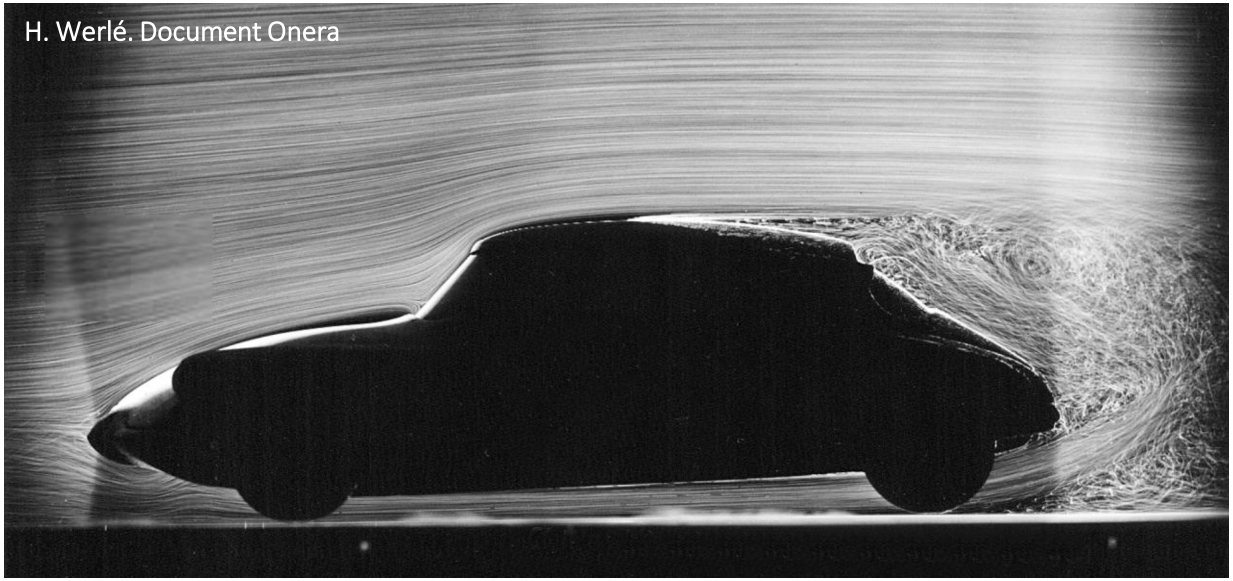
Overview

- General issues, passive *vs* active…
- Control issues: optimality and learning *vs* robustness and rough model
- Model-based control: linear model, nonlinear control
    - Linear model, identification
    - Sliding Mode Control
    - Delay effect
    - Time-delay systems
- Introduction to delay systems
    - Examples
    - Much a do about delay? Some special features + a bit of maths
    - Time-varying delay
- Model-based control: nonlinear model, nonlinear control
    - Overview of MF’s PhD: Sliding Mode Control
    - Application to the airfoil
    - Application to the Ahmed body (MF and CC’PhDs)

…

- Machine Learning and model-free control: + 4h with Thomas Gomez

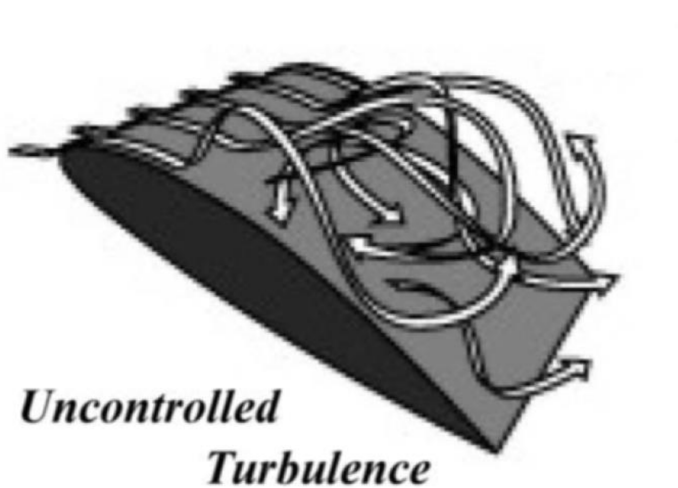
Passive flow control



but, also...

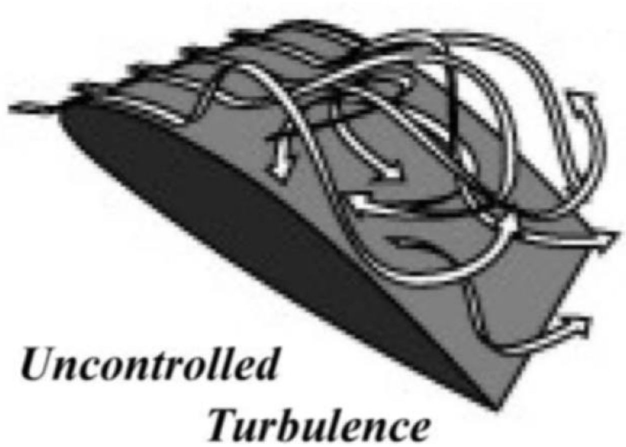
https://www.lanouvellerepublique.fr/vienne/des-avions-inspires-des-baleines-et-des-requins

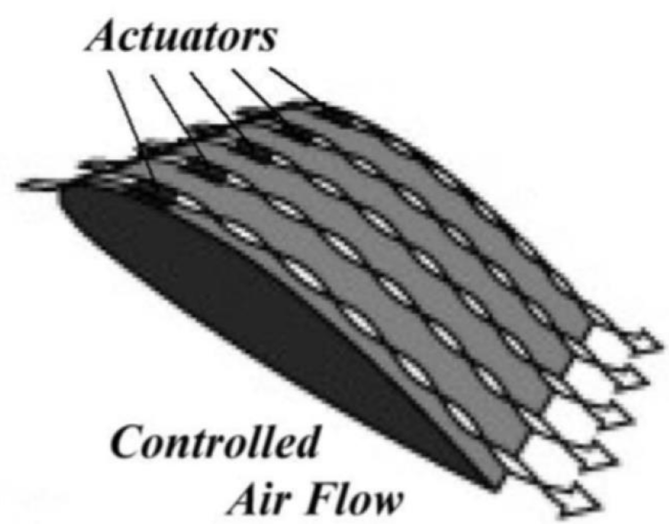
Active flow control?



High turbulence
High energy loss
High vibrations
Lower lifetime of the components

Active flow control?

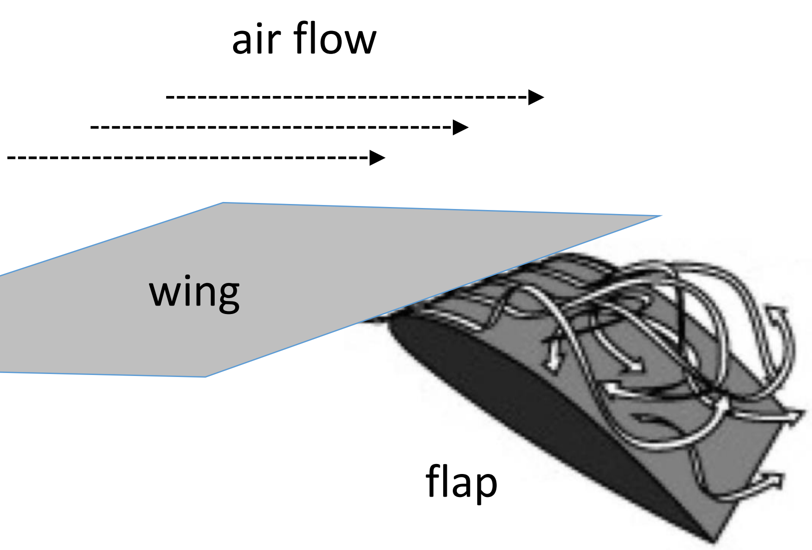




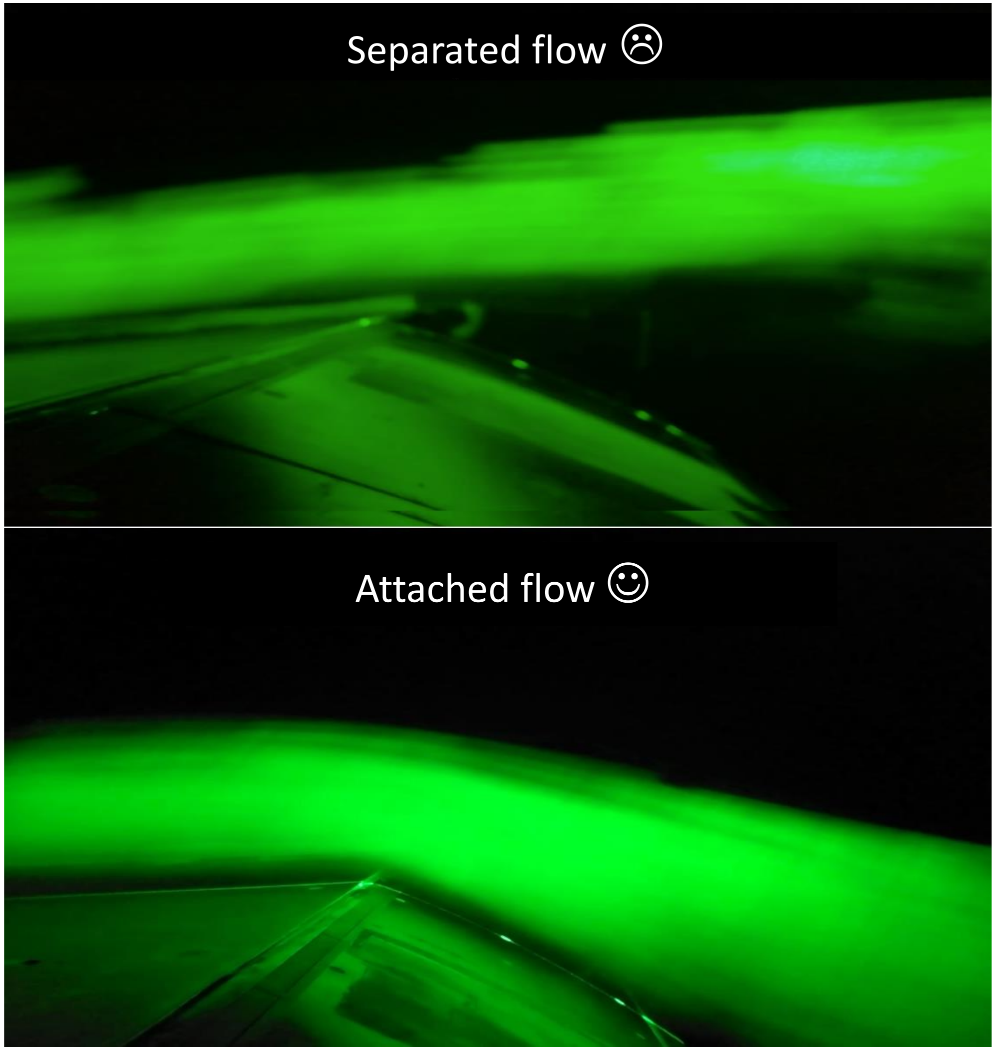
High turbulence
High energy loss
High vibrations
Lower lifetime of the components

Low turbulence
Low energy loss
Low vibrations
Higher lifetime of the components

Active flow control



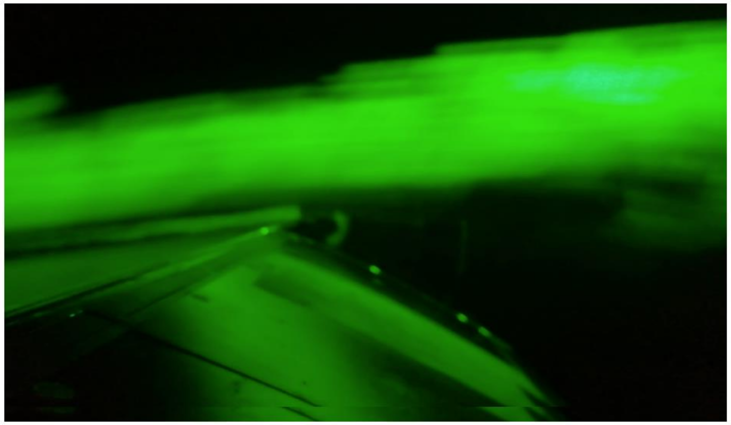
Tomography →

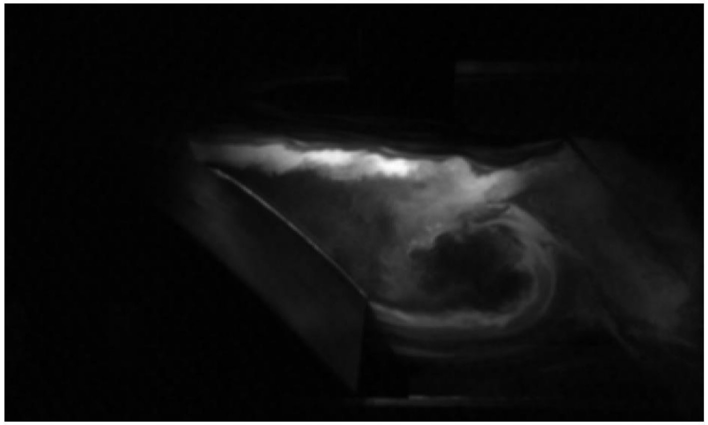


Active flow control

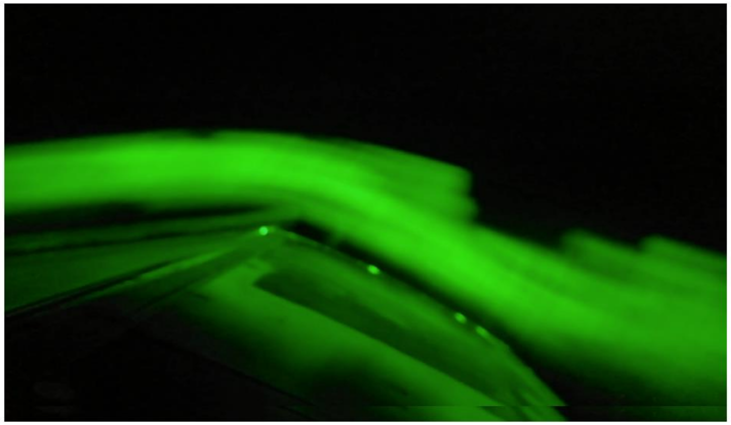
PhD Feingesicht 2017

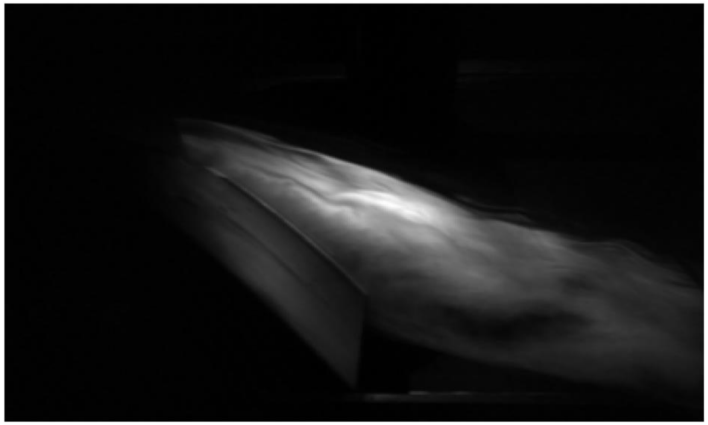
PhD Chabert 2014





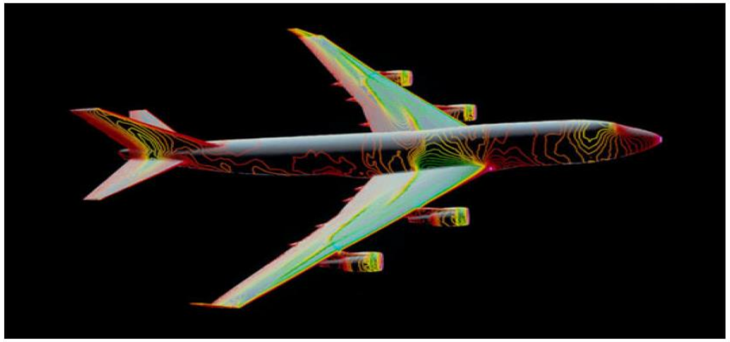
Visualisation of a flow without control





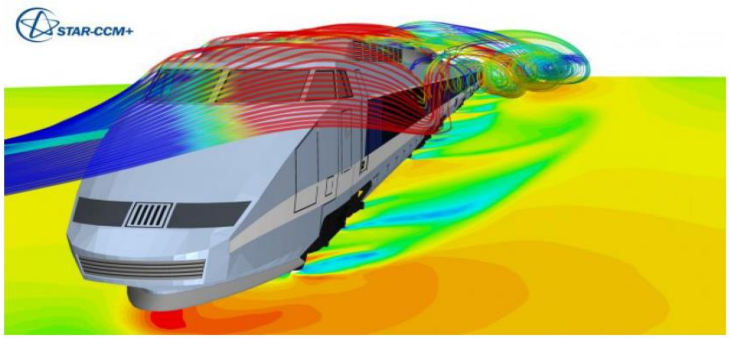
Visualisation of a flow with periodic (open loop) control (1 Hz, DC 50%)

Application domains

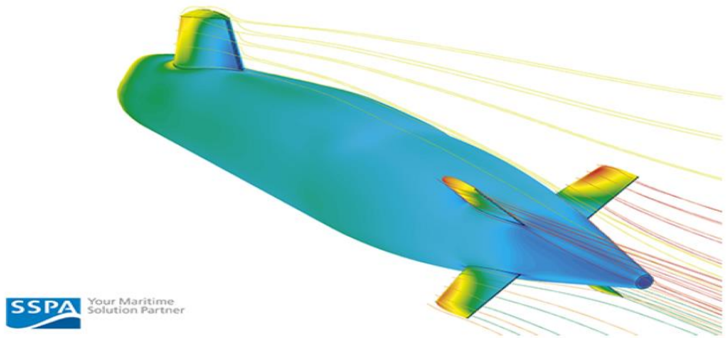


(a) Plane (Credit: NASA)

(b) Car (Credit: R. G. Bulmahn)

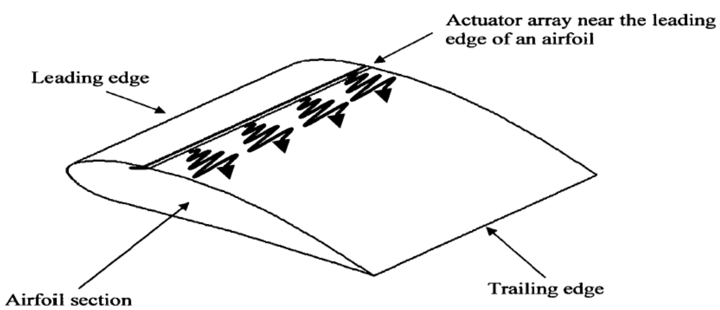


(c) Train (Credit: Siemens)

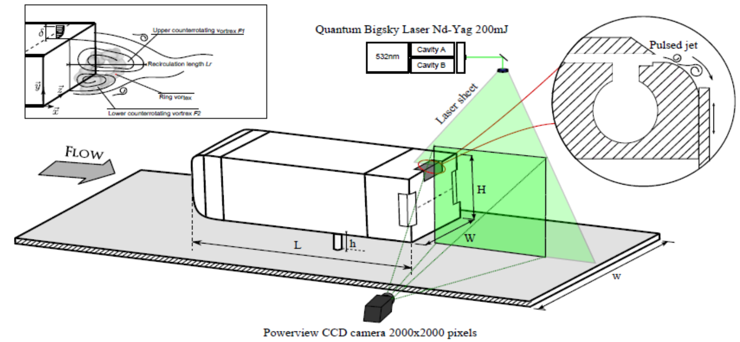


(d) Submarine (Credit: SSPA)

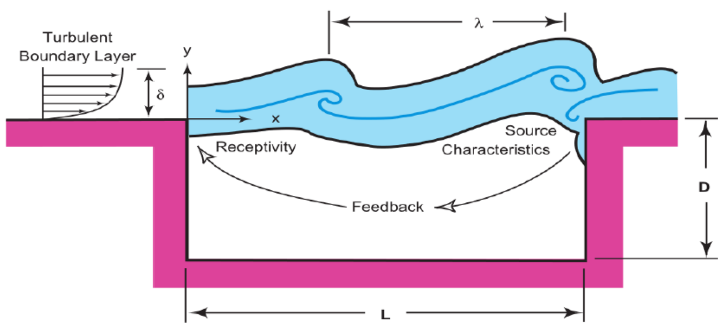
Application domains



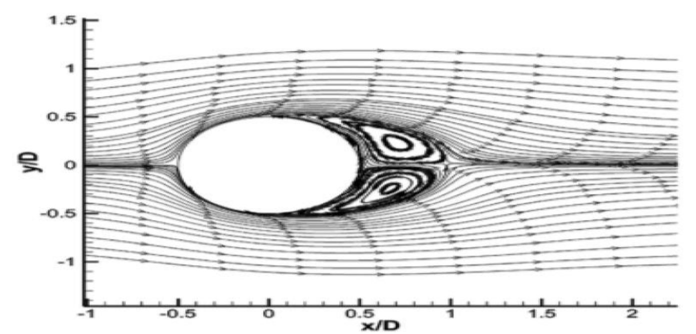
(a) Flap (Raghu 2013)



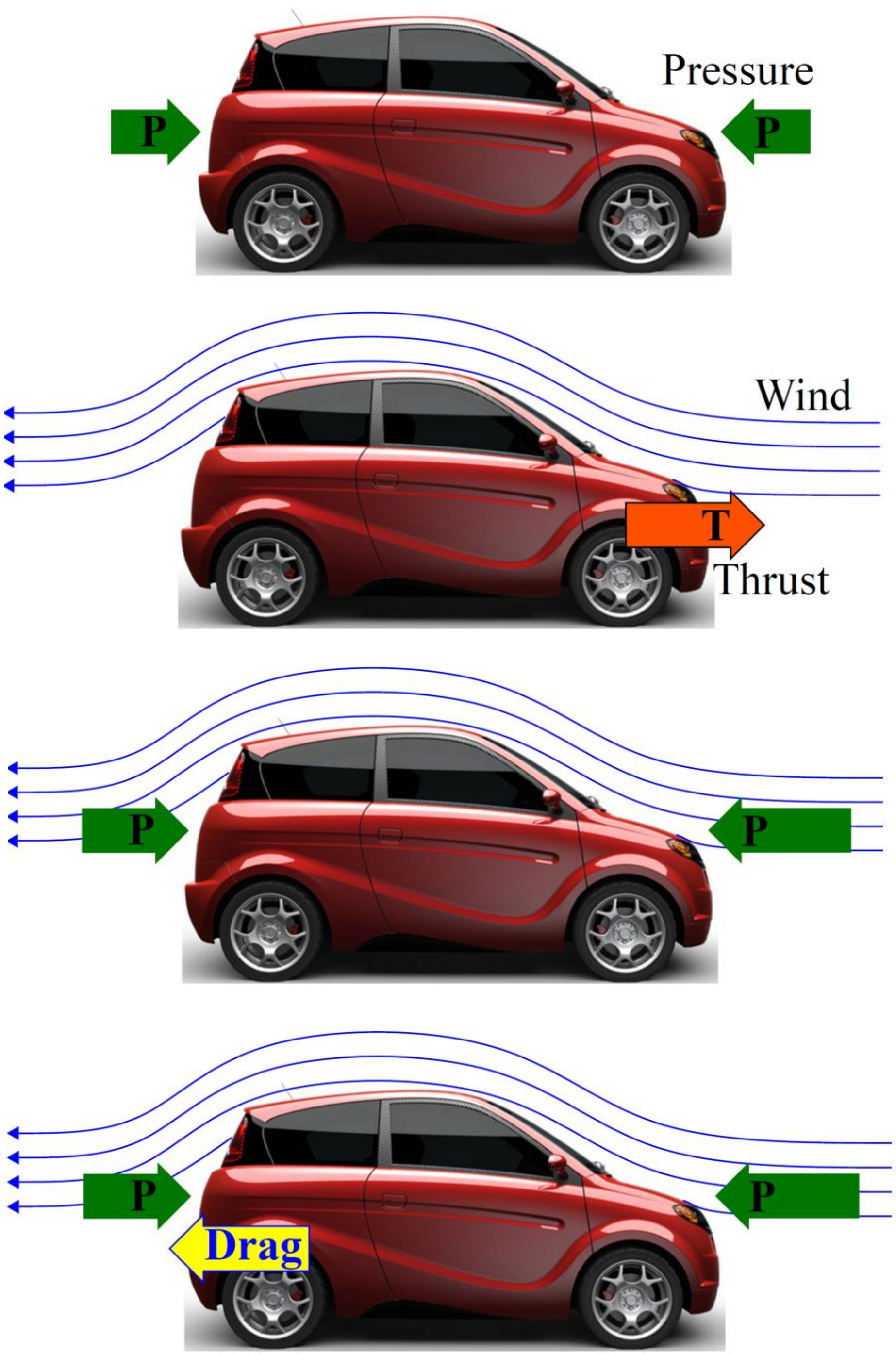
(b) Ahmed body (Khan and Umale 2014)



(c) Cavity (Cattafesta III et al. 2008)



(d) Bluff body (Liu, Wei, and Qu 2013)



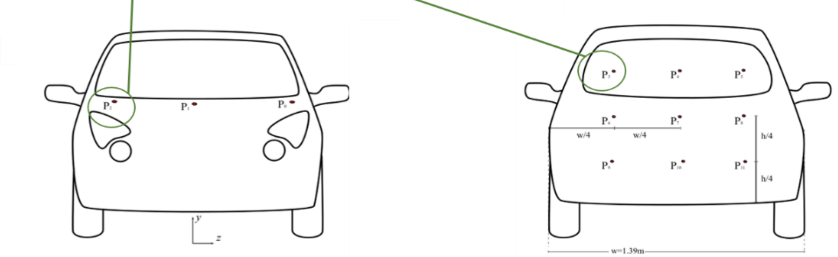
I'm no mechanical engineer

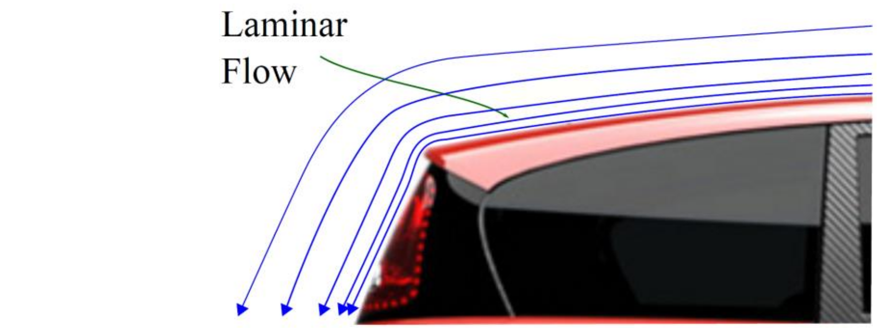
→ please help me!

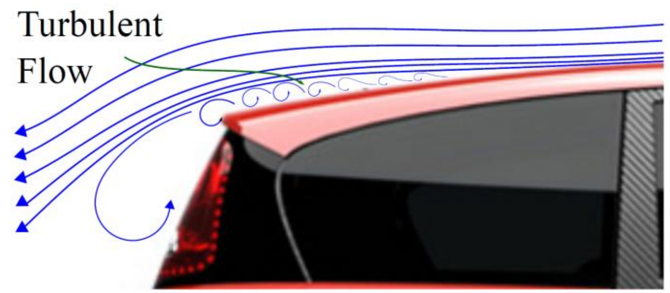
(did I get it right?)

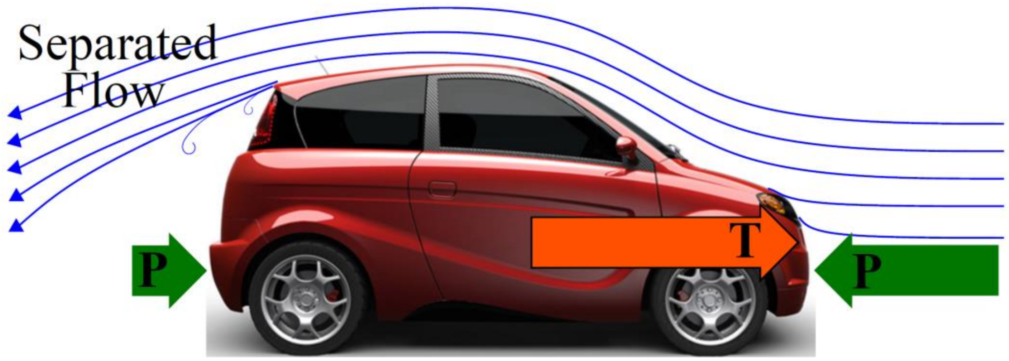
Drag estimation: Onorato's relation

$$F_D = \iint_{S_W} (P_\infty - P_{S_W})\, d\sigma - \frac{\rho U_\infty^2}{2} \iint_{S_W} \left(\frac{U_y^2}{U_\infty}^2 + \frac{U_z^2}{U_\infty}^2 \right) d\sigma + \frac{\rho U_\infty^2}{2} \iint_{S_W} \left(1 - \frac{U_x^2}{U_\infty}^2 \right) d\sigma$$





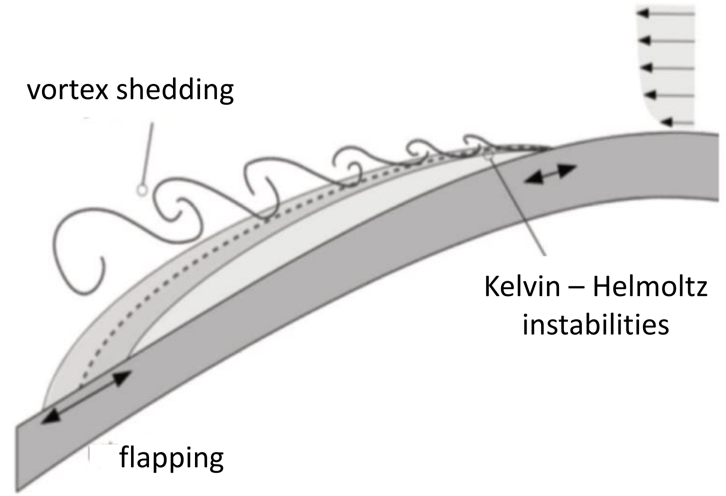




I'm no mechanical engineer

→ please help me!

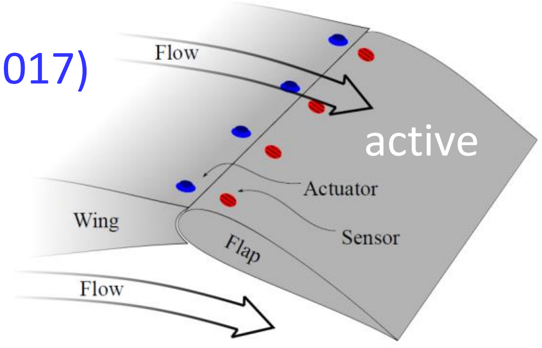
(did I get it right?)



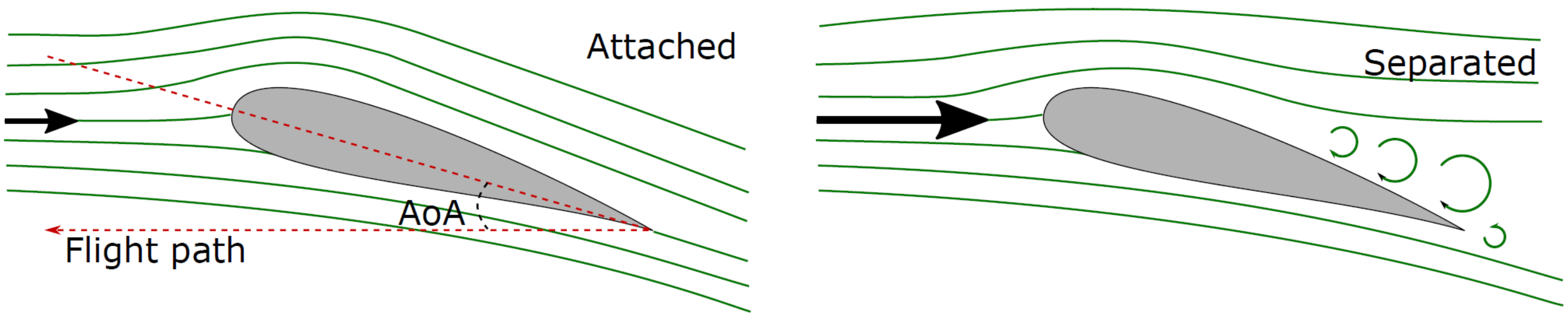
Flow control: Passive *vs* Active

- Flow control started with the works of Stalker (Stalker 1936 and Stalker 1949)
- Historically, separation was hanlded by passive flow control (Fish and Lauder 2006, Hak 2006, Volino 2003)
- Active flow control is an answer to the issues of passive flow control (Scott Collis et al. 2004)
- Numerous types of actuators and sensors have been used in active flow control (Cattafesta et al. 2003)
- Modeling in flow control is often based on data and uses methods such as POD (Lumley 1967) or input-output models (e.g. ARMAX (Hervé et al. 2012))
- Successful algorithms in flow control include Genetic Programming (Duriez, Brunton, and Noack 2016), Slope Seeking (Chabert et al. 2014), PID (Raibaudo 2015)

… and Sliding Mode Control (Feingesicht 2017)



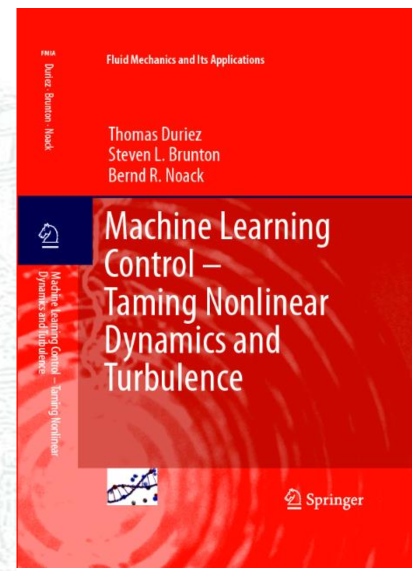
Flow control: Passive *vs* Active



Active flow control: Positioning

- Open loop: (periodic), not robust, not precise, energy consuming
- Linear+PID: not robust, not precise wrt perturbations, no proof of stability
- *Machine Learning*: needs learning, no proof of stability, robustness?
- SMC+delay model… to be presented here

https://www.univ-valenciennes.fr/LAMIH/en/2nd-machine-learning-control-workshop



Active flow control: Positioning

.	*Pros*	*Cons*
► Model-free (machine learning)	saves identification time optimality (at least in open loop) easy to implement … fashionable (magic of A.I.) ;)	induces training time no proof of stability no proof of robustness
► NL+D model (bilinear-delay + SMC)	∃ theoretical proofs robustness easy to implement … we did it ;)	identification (nonconvex opt.) mathematics of control
► Both… today :	surpass passive aerodyn.	TBD: energetic trade-off? commercial issue = actuators

Active flow control: model-based *vs* model-free

AFC is divided in two main categories. The first one is model-free control. Among others, recent developments in model-free techniques led to controllers based on machine learning techniques and showed promising results. However, machine learning requires numerous experiments before being efficient and the reliability and convergence of the algorithms are not well proven. The second category is model-based control. Model-based robust control of separated flows remains of particular interest and can be implemented on real systems without too much complexity if the model is chosen to be sufficiently simple. But it requires to have a model of the flow, may it be from physical equations or from identification. The first approach would be to use partial differential equations, namely the Navier-Stockes Equations (NSE), but this implies complicated (or even impossible) online calculations and the way to design controllers/observers remains open.

The alternative proposed in this work is to use ”grey-box” identification techniques so to derive a simpler model that can be useful for control purpose. The model suggested is a bilinear, delayed difference equation which is able to catch non-linear mechanisms. Such a model will be shown to be quite realistic in an identification perspective. It is much simpler than NSE, however remains nonlinear and behaves in an infinite dimensional space.

A regional consortium around Lille

CPER ELSAT2020 (+ FR TTM)

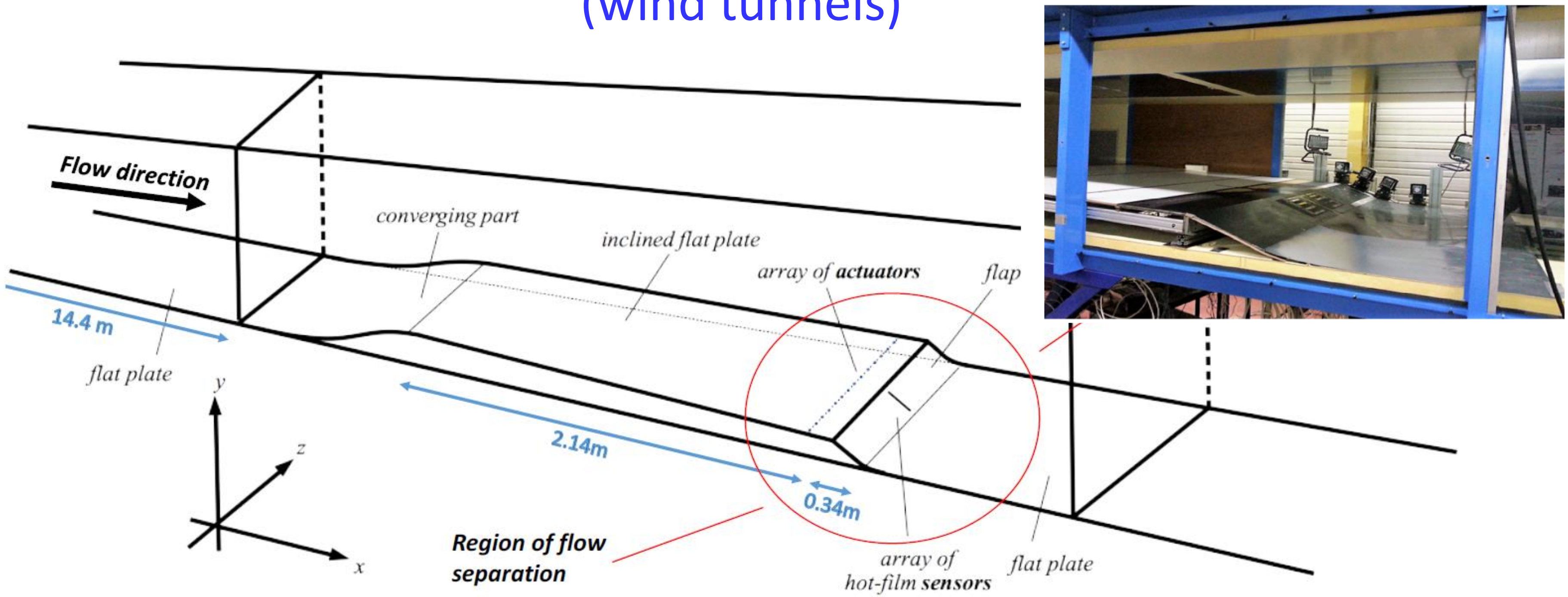
- Aeronautics (ONERA)
- Micro-NanoTechnologies (IEMN)
- Fluid mechanics (LML, LAMIH)
- Control: CRIStAL / Inria Non-A

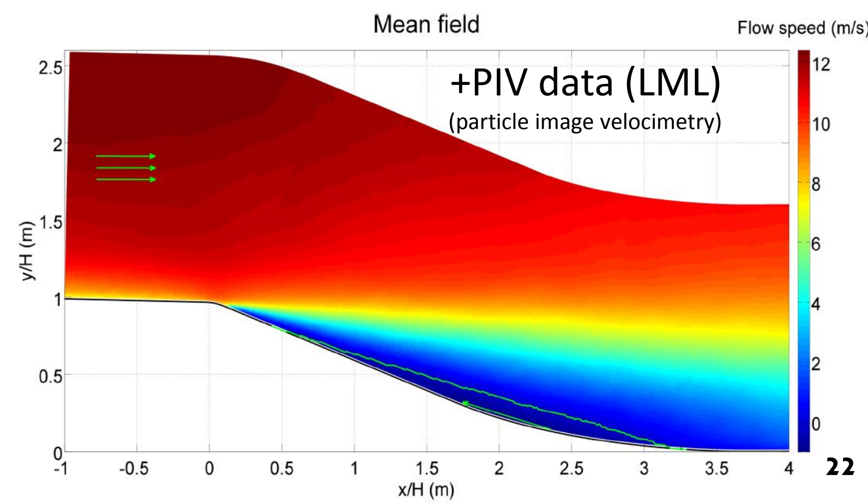
+ UPR PPRIME (Poitiers, F. Kerhervé)

PhD Maxime Feingesicht 11/12/2017 (Andrey Polyakov, Franck Kerhervé, J.P. Richard)

Very Hardware

(wind tunnels)

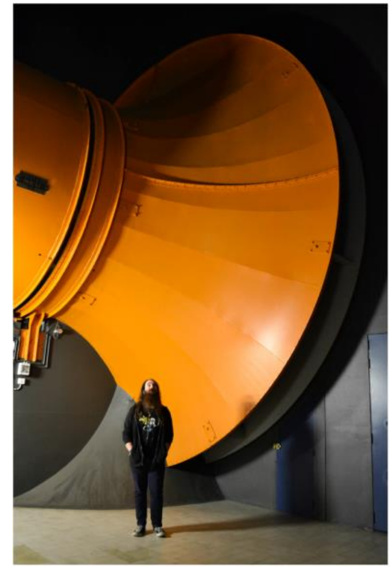




Laboratoire de Mécanique des Fluides de Lille
Kampé de Fériet

Very Hardware

(wind tunnels)

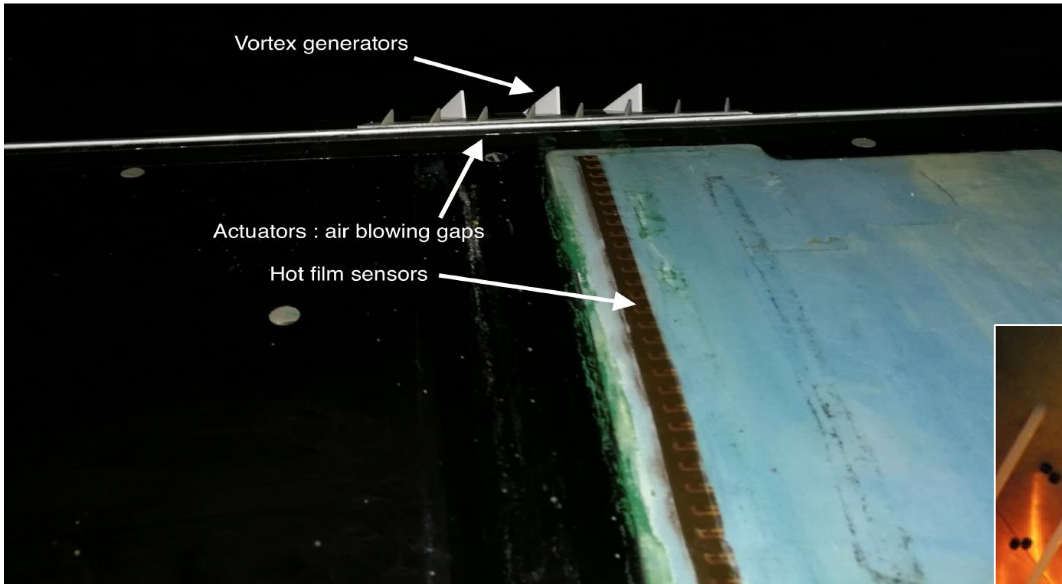


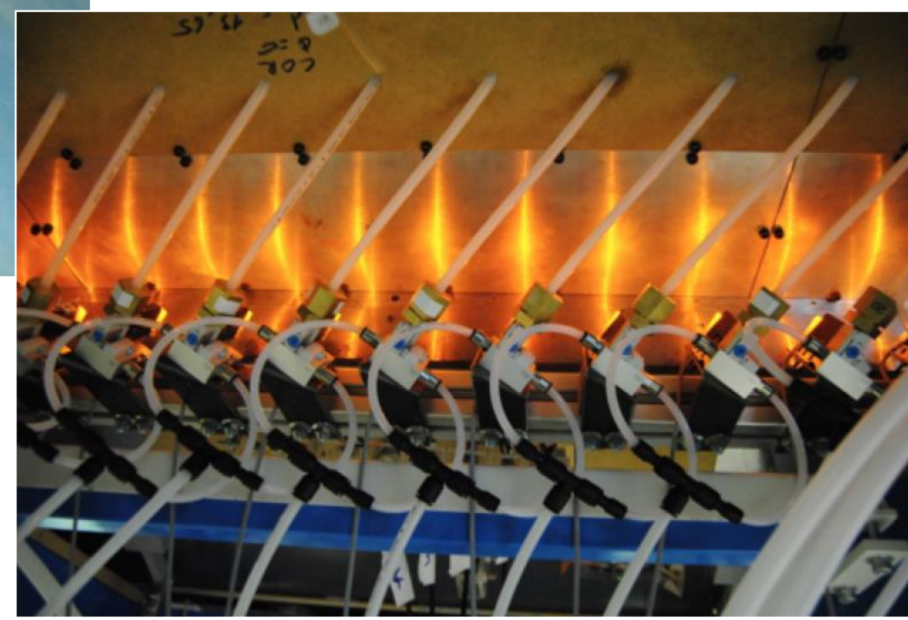
Credit: article "Améliorer l'aérodynamisme des avions en contrôlant l'écoulement de l'air" made by INRIA

Flow Control: Airfoil in the Onera L1 wind tunnel

*Hard*ware

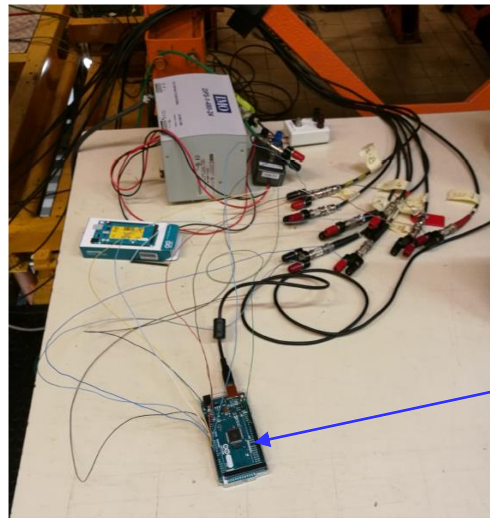
(sensors, actuators)



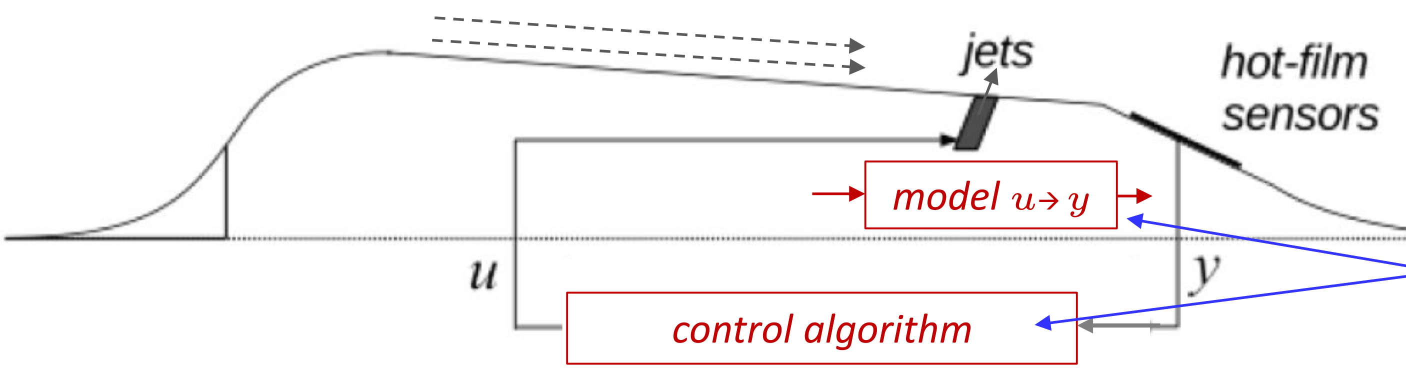


*Soft*ware!

(control law = calculation code)



here we are ;)



yes, right there :)

Usual model for fluid mechanics

Navier-Stokes Equations
3 – dimensional – unsteady

Glenn Research Center

Coordinates: (x,y,z)
Velocity Components: (u,v,w)

Time : t
Density: ρ
Total Energy: Et

Pressure: p
Stress: τ

Heat Flux: q
Reynolds Number: Re
Prandtl Number: Pr

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$
$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx} + v\,\tau_{xy} + w\,\tau_{xz}) + \frac{\partial}{\partial y}(u\,\tau_{xy} + v\,\tau_{yy} + w\,\tau_{yz}) + \frac{\partial}{\partial z}(u\,\tau_{xz} + v\,\tau_{yz} + w\,\tau_{zz})\right]$$

Concerns:
- existence of (strong) solutions in dim 3 ? (no formal proof)
- no general control theory for such nonlinear PDEs
- real-time issues (even for 2D simulation…)

Question: how to control *that*?

Navier–Stokes Equations

3 – dimensional – unsteady

Glenn Research Center

Coordinates: (x,y,z)

Velocity Components: (u,v,w)

Time : t

Density: ρ

Total Energy: Et

Pressure: p

Stress: τ

Heat Flux: q

Reynolds Number: Re

Prandtl Number: Pr

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$
$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y}(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z}(u\tau_{xz} + v\tau_{yz} + w\tau_{zz})\right]$$

Answer: don’t control *that.*

Simpler PDEs?

In order to simplify the study of flows, many other PDEs were developed for more specific cases. For example, we can cite the Burgers equation (see Equation (1.12), [20]) used to study the combined effects of nonlinear advection and diffusion and as a simple yet inaccurate way to approach turbulence and the Korteweg–de Vries equation (see Equation (1.13), [86]) that is used to describe the evolution of long one-dimensional waves called solitons.

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \nu\frac{\partial^2 v}{\partial x^2} \tag{1.12}$$

$$\frac{\partial v}{\partial t} + \frac{\partial^3 v}{\partial x^3} + 6v\frac{\partial v}{\partial x} = 0 \tag{1.13}$$

1.4.2 Reduced-order models

1.4.2.1 Petrov-Galerkin method

1.4.2.2 Finite Differences Method

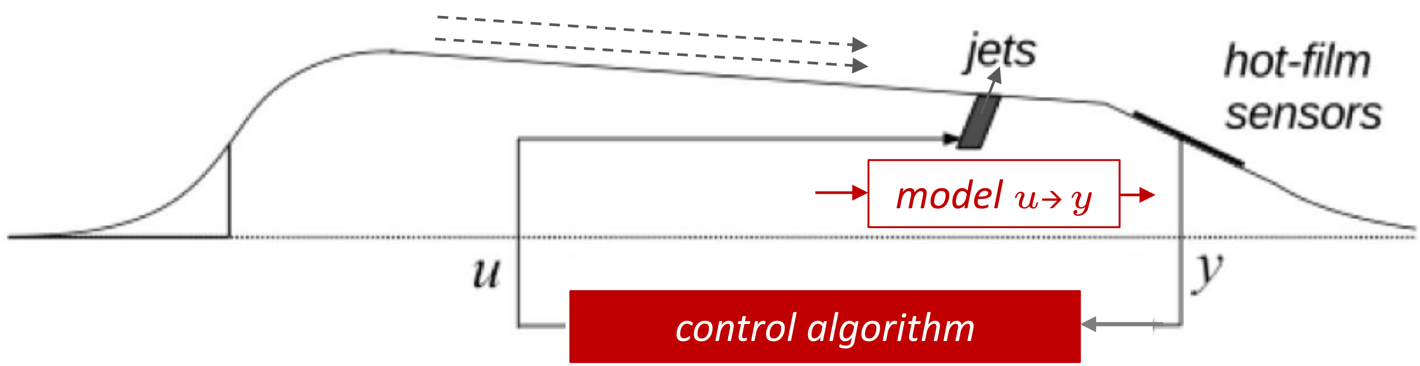
1.4.2.3 Special case of Proper Orthogonal Decomposition (POD-Galerkin)

see Maxime’s PhD, pdf p.50-56.

don’t control *that*, either.

Input – Output flow Control

General ideas for control engineering:
- start with the simplest model = the one you can control?
- bad model quality? Compensate with robust control
- if still needed, complexify the model... and the control



Advantages:
- SISO (1 input – 1 output)
- 3D dynamics → 1D dynamics (actuator → sensor)
- local models? (linearization, then PID)

Still various issues:
- on/off control (actuation technology)
- nonlinear model (compressible fluid)
- infinite dimension (diffusion)

... but rather control *this*.