# *EFFECT OF A POROELASTIC LAYER ON LIFT AND DRAG OVER AN AIRFOIL*

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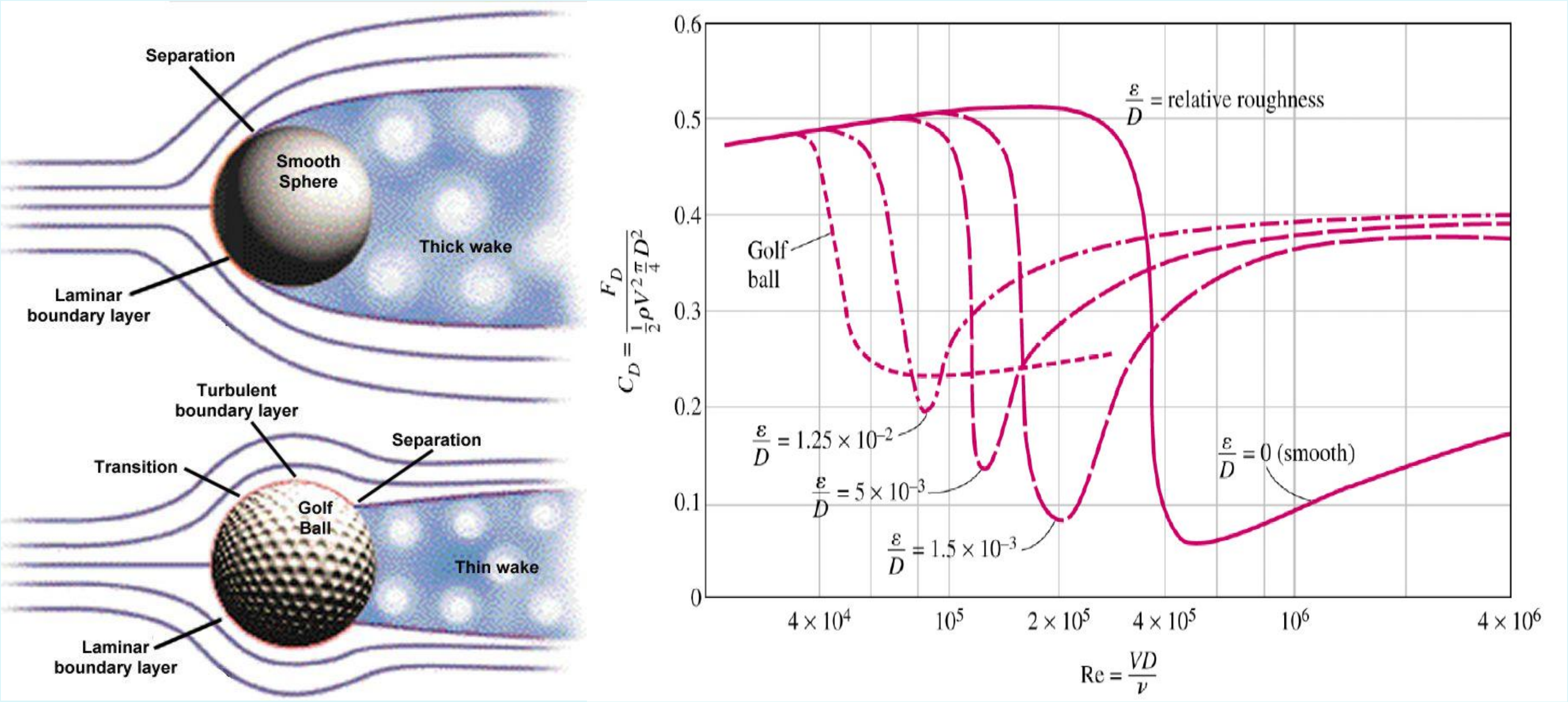
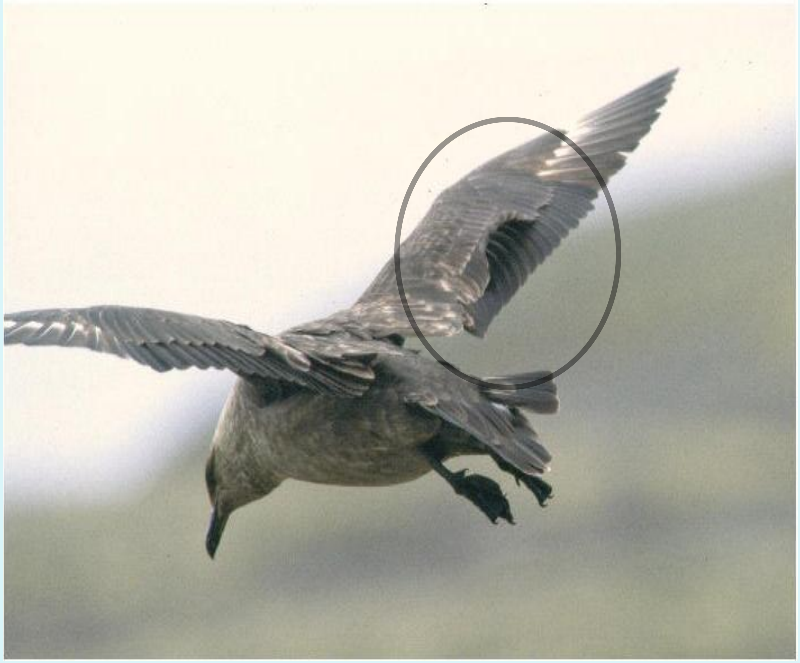
Focus on passive actuators, what works, why it does, how can we select and "optimise" actuators for lift/drag purposes, etc.?

# Reducing pressure drag by a passive technique …

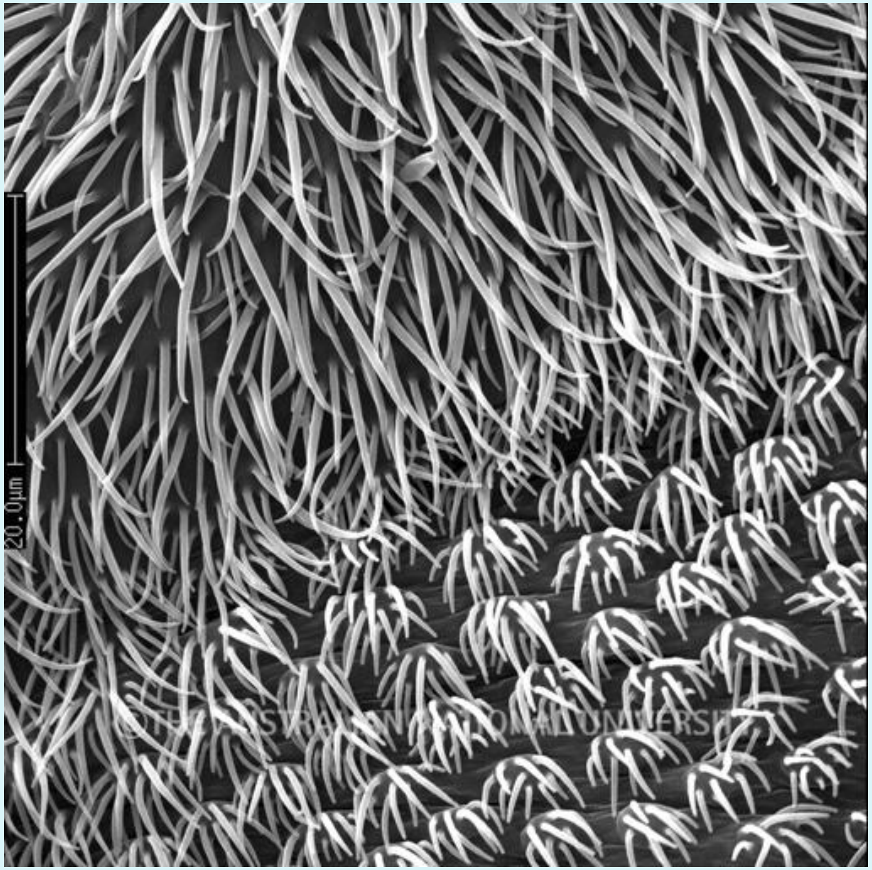


# “Coverts” feathers …

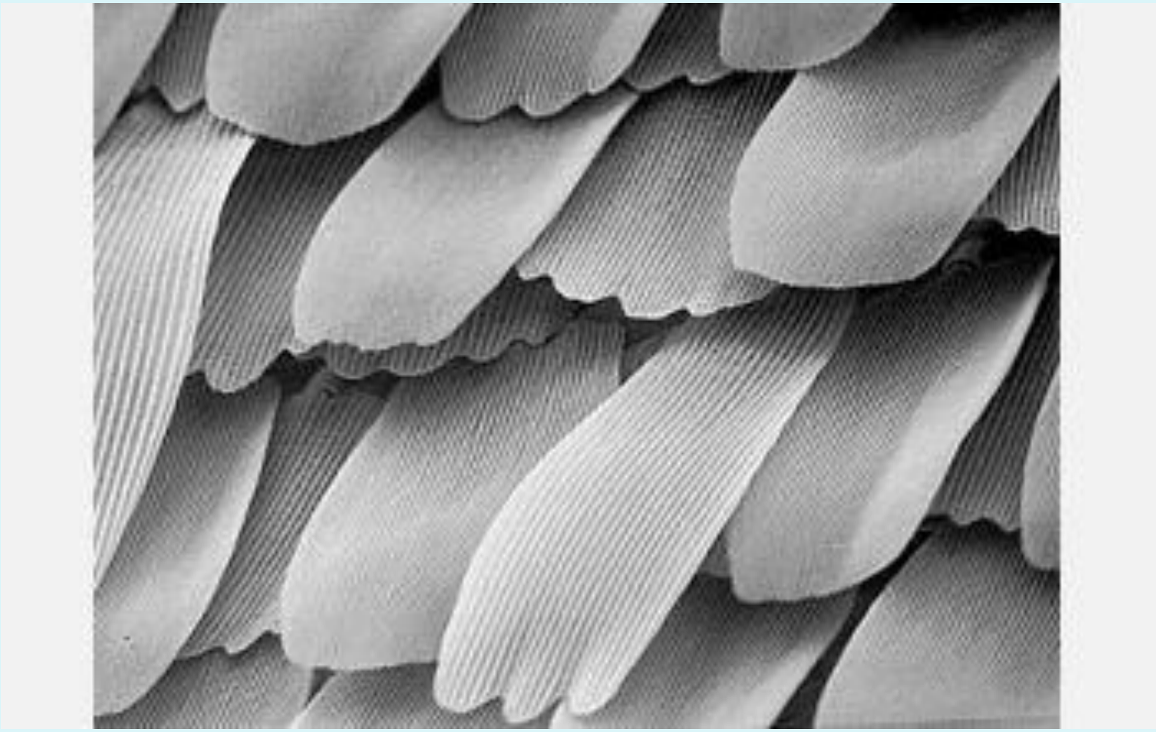



# … and other appendages are the norm

mosquito body

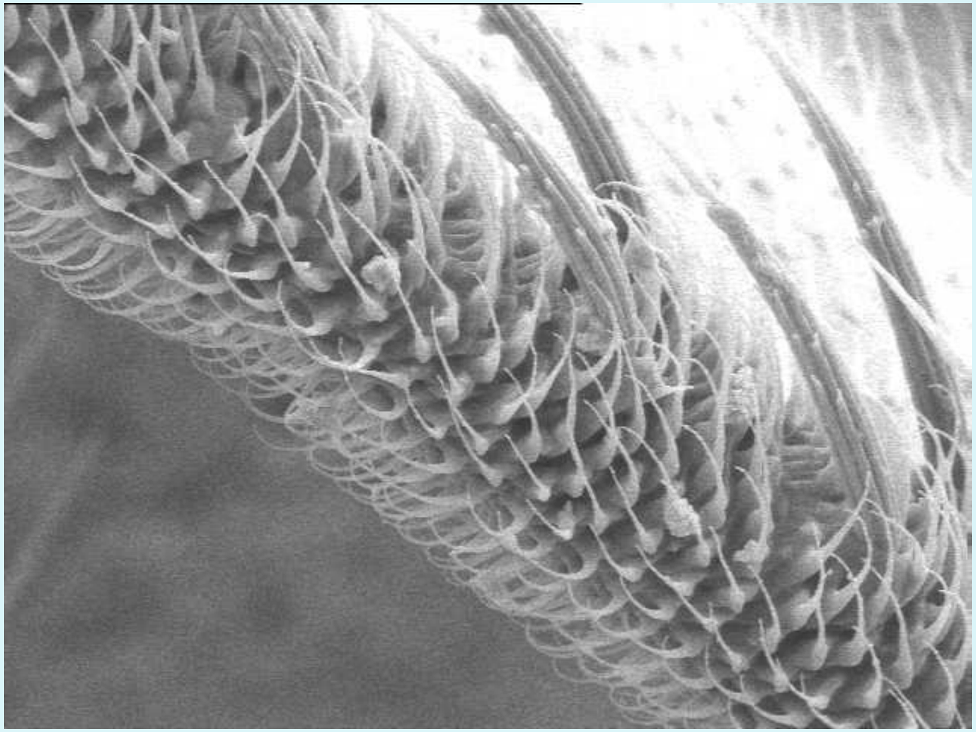


# … and other appendages are the norm



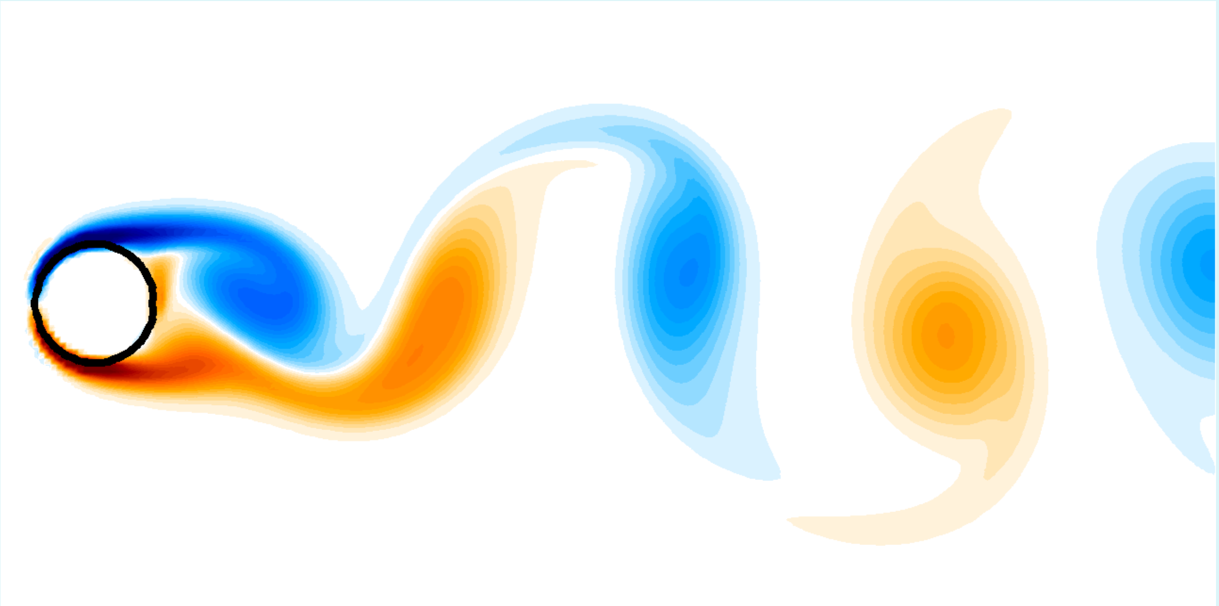
butterfly scales

# … and other appendages are the norm



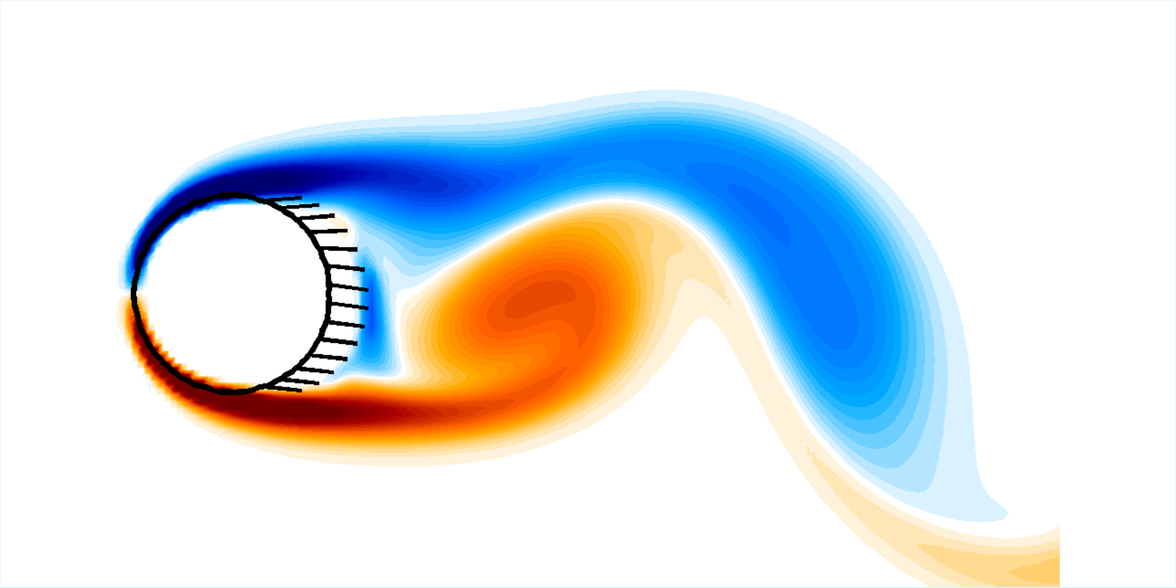
fly wing

# Passive control via “append-actuators”



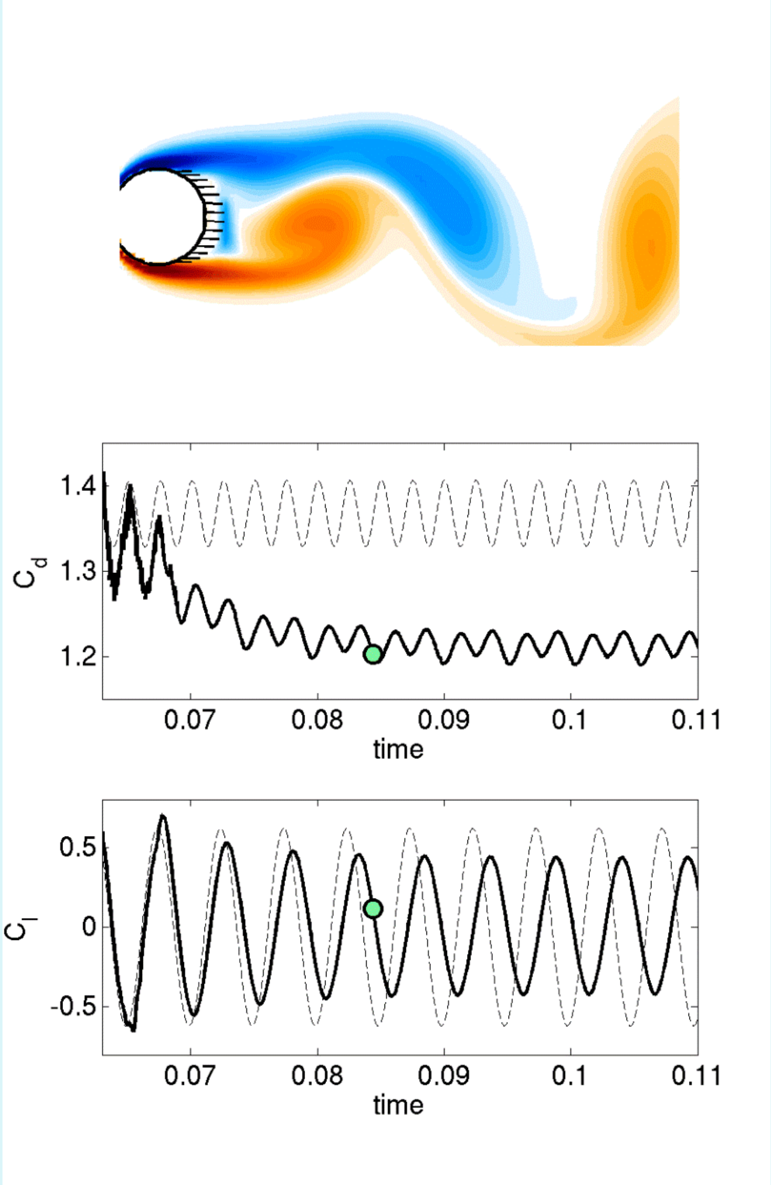
Re = 200

# FSI

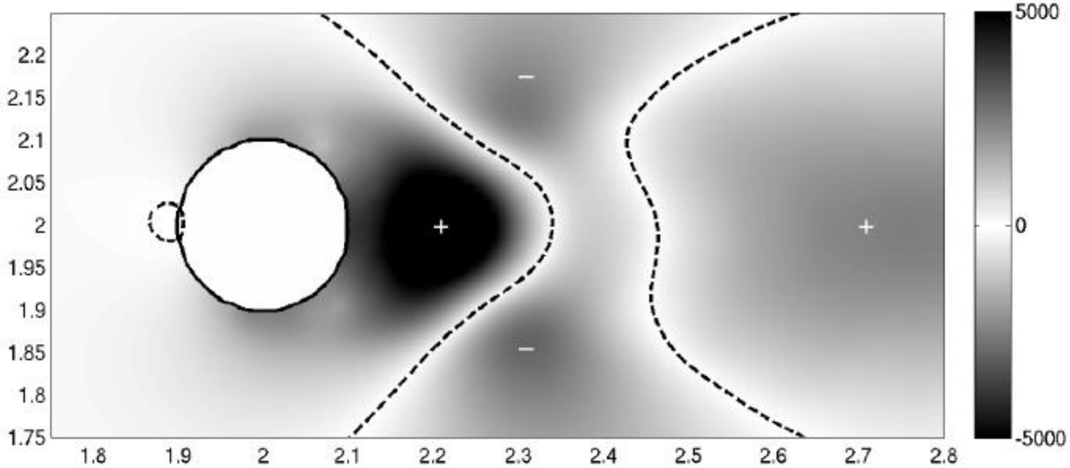


$C_d$ ↘

amplitude of $C_l$ oscillations ↘

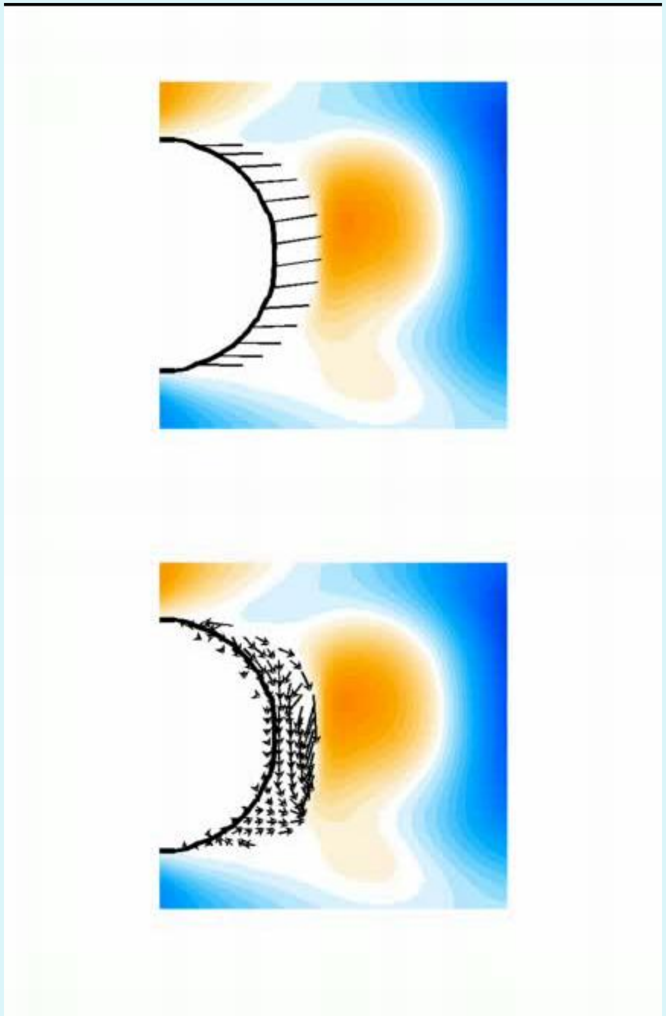


# What happens?



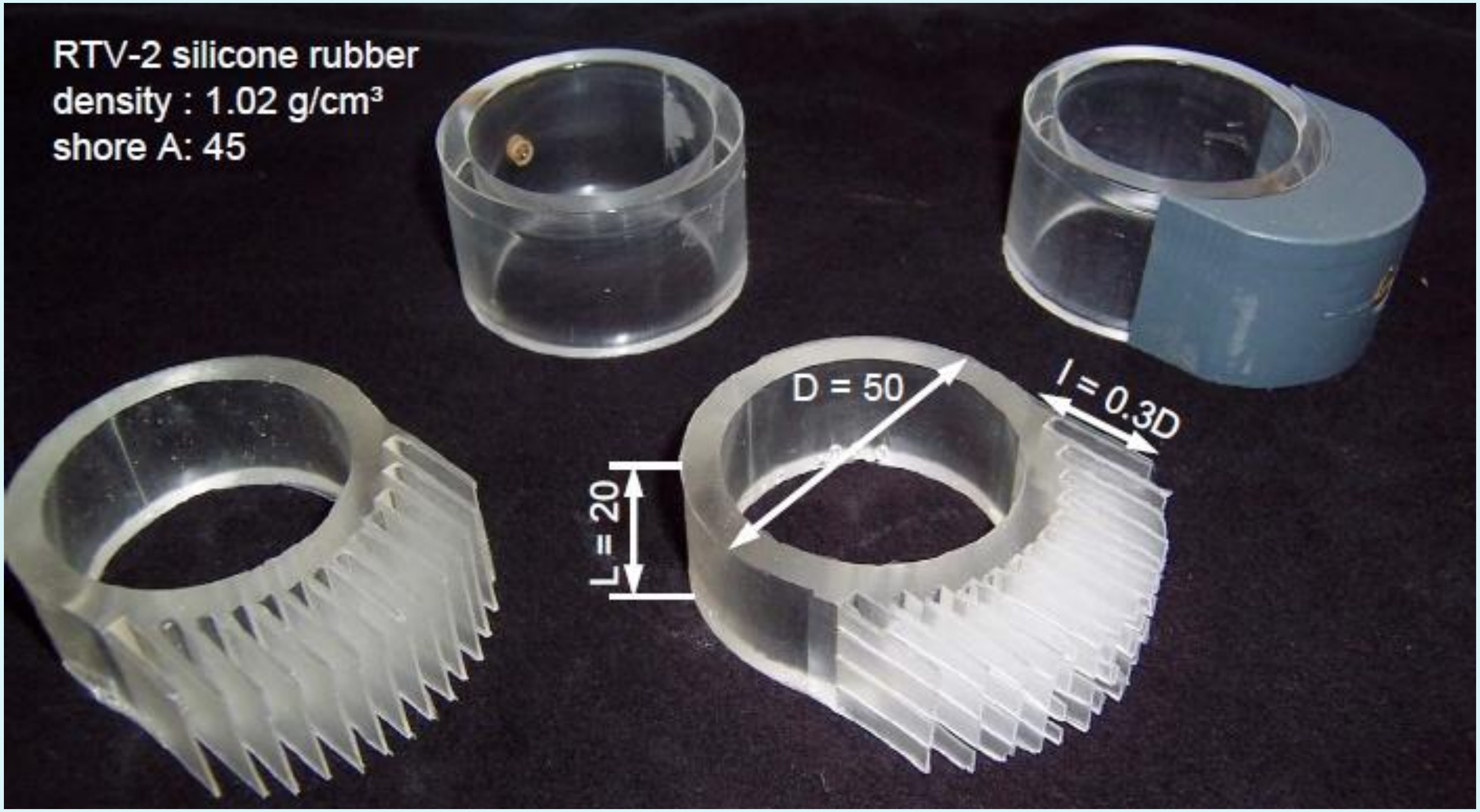

Difference of time-averaged pressure field

<P with hair>-<P ref>

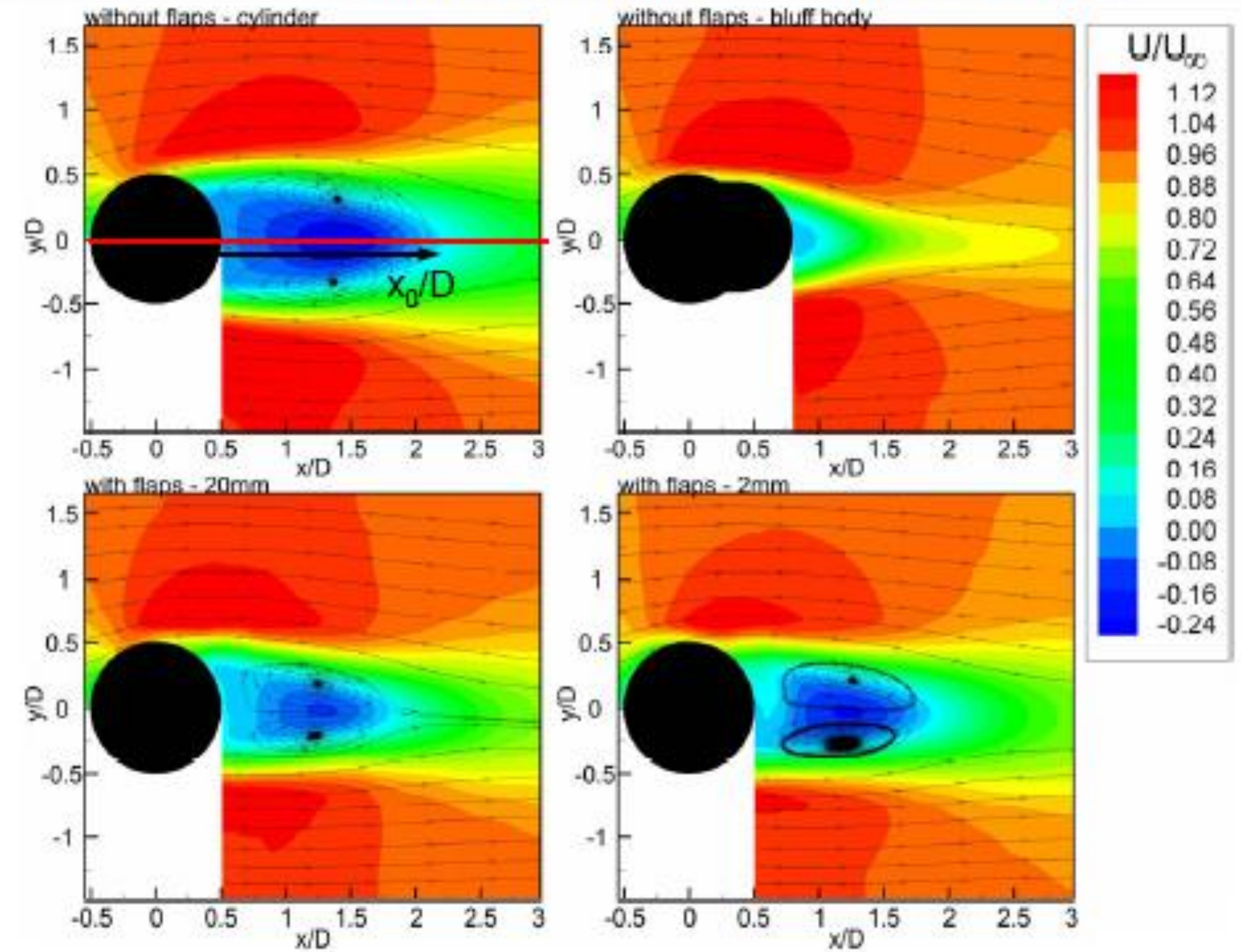


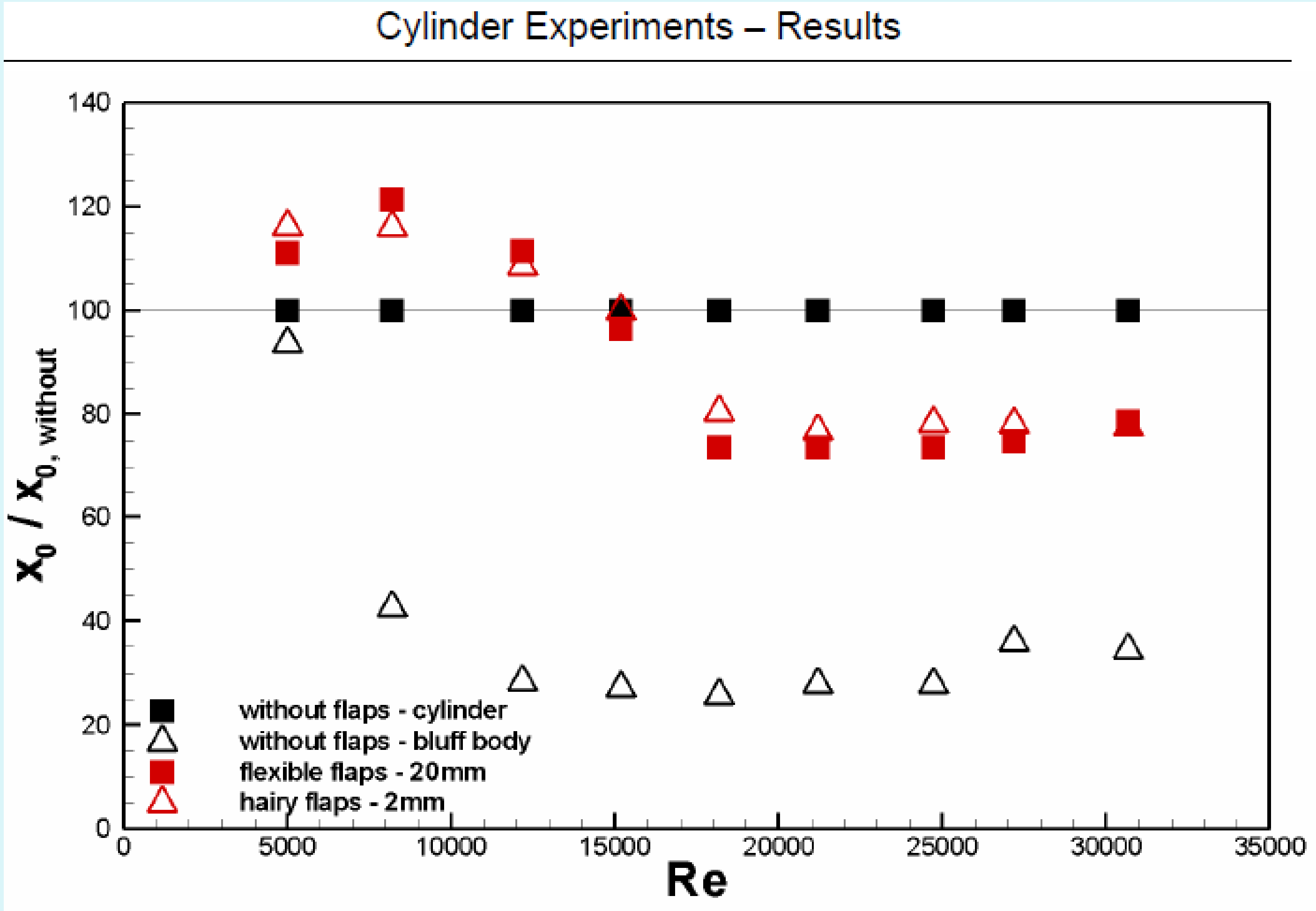
Favier *et al*, JFM 2009

# For larger Re numbers, there are the experiments in water and oil channels by Prof. Ch. Brücker

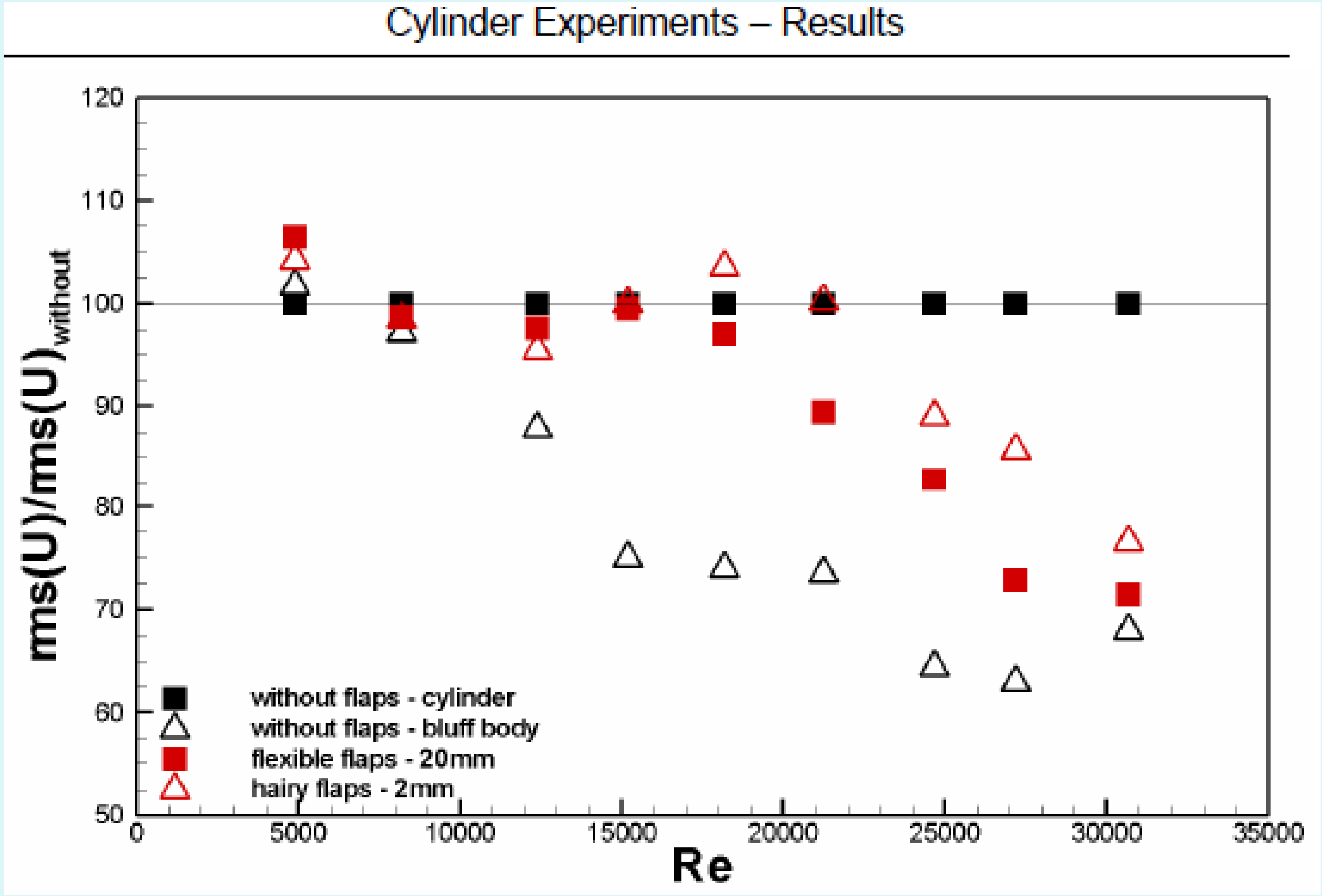


# Cylinder Experiments – Results Re = 27200





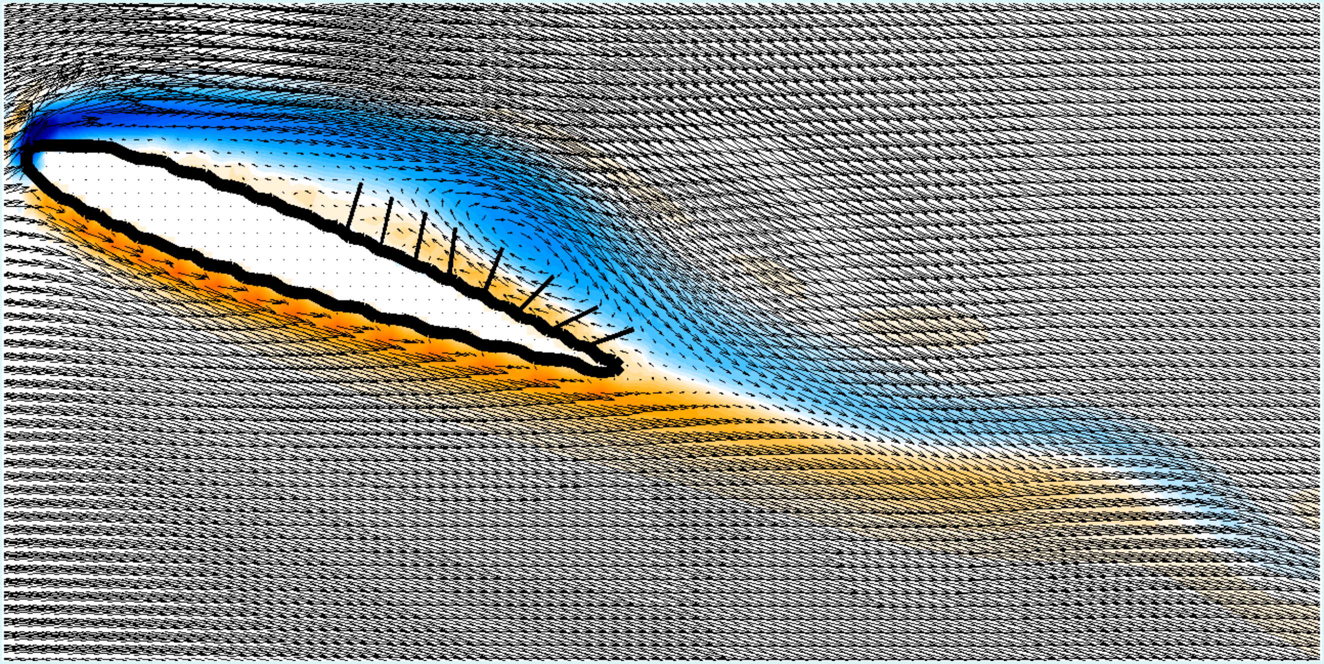

Flexible and hairy flaps produce a comparable result: recirculation area elongated for Re < 15000, shortened for Re > 15000



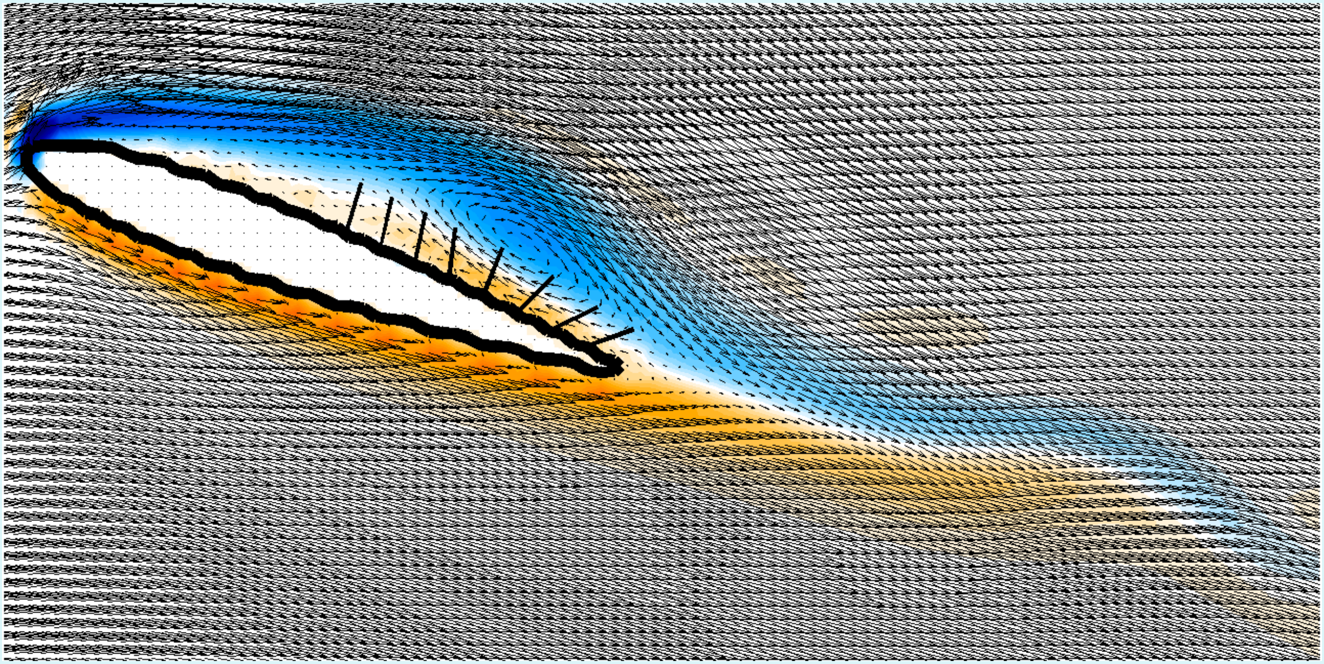

… plus reduced flow fluctuations for Re > 15000

Clear effect on the cylinder wake
→ effect on drag

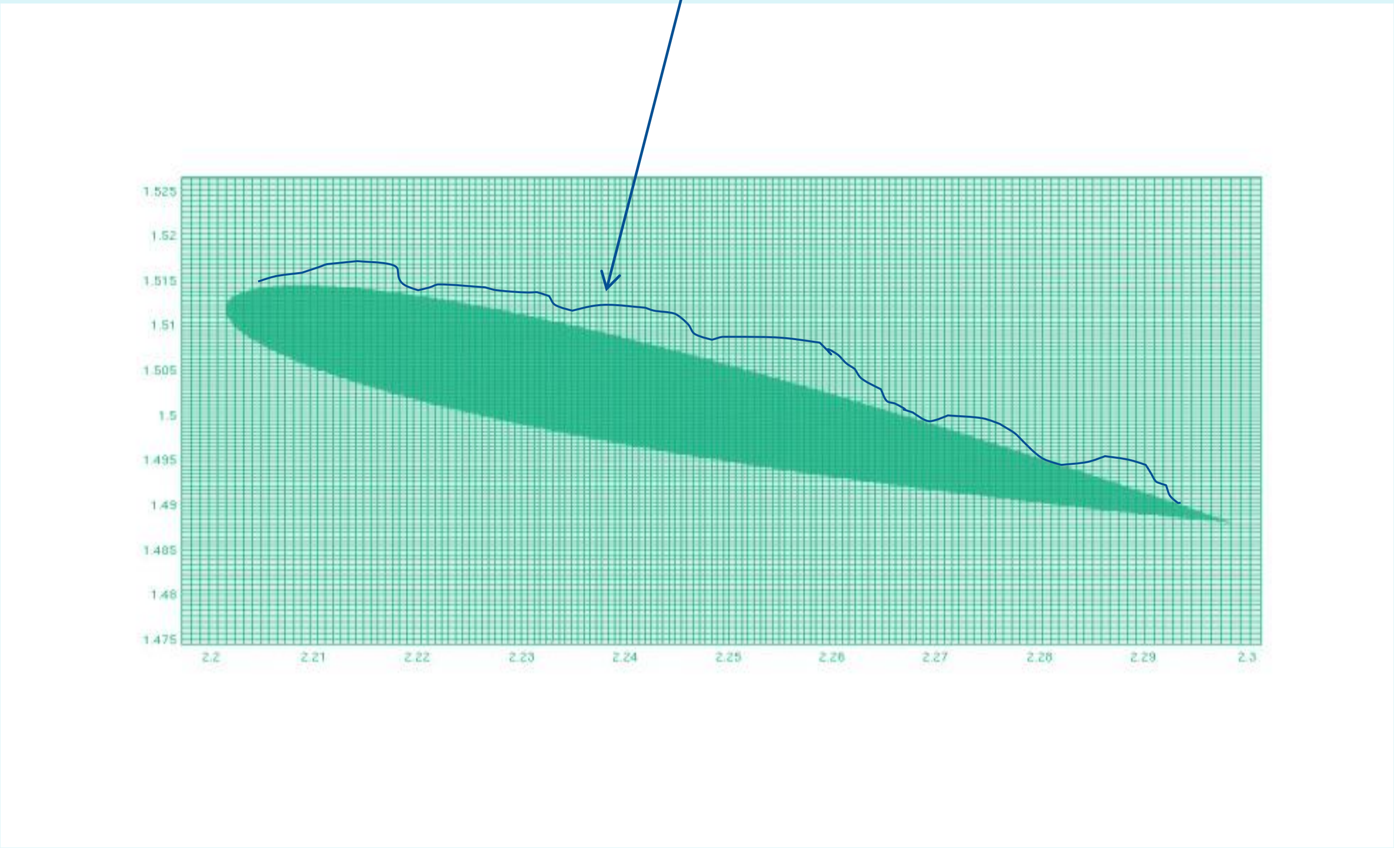
# New goal: effect on lift and drag over an airfoil via a *passive, poroelastic* layer



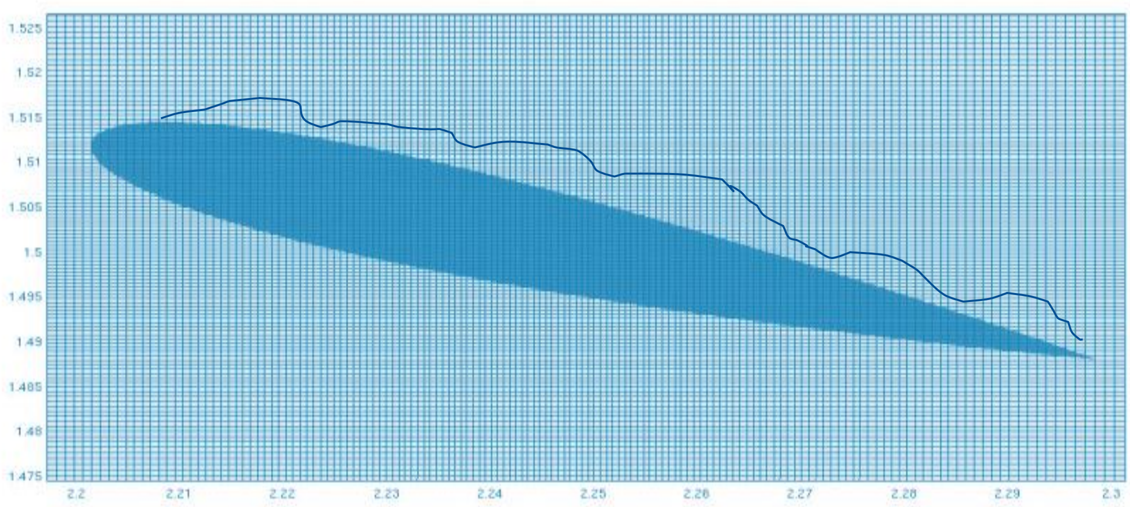
# *HAIRFOIL !*



Goal: put a *poroelastic layer* on the suction side of an airfoil to affect the separated region and the wake



How can we model the layer (made of fibers, hence porous and compliant)?



# Options:

| | | | |
|---|---|---|---|
| **Experiments** | **Poroelasticity theory** | **NS IBM simulations** | **Low order model** |

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| | | | |
|---|---|---|---|
| **Experiments** | **Poroelasticity theory** | **NS IBM simulations** | **Low order model** |

- Berlin, Prof. I. Rechenberg
- Freiberg, Prof. Ch. Brücker
- Orléans, Prof. A. Kourta
- Genova

# Experiments (Berlin)

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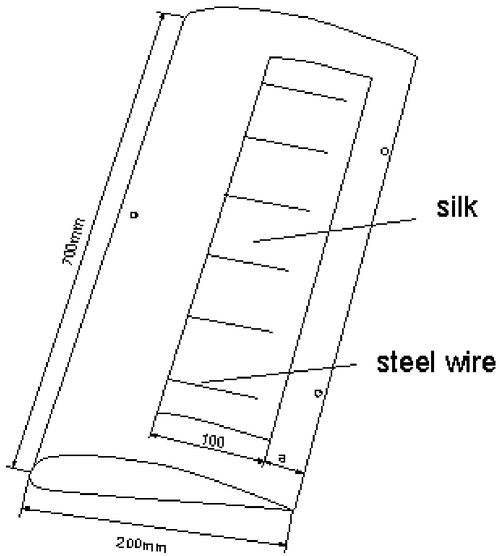
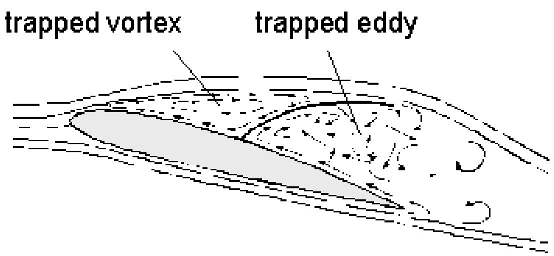
aerofoil with silk flaps




flow visualisation




Prof. Ingo Rechenberg, TU Berlin
http://www.bionik.tu-berlin.de/institut/xs2vogel.html

# Experiments (Berlin)

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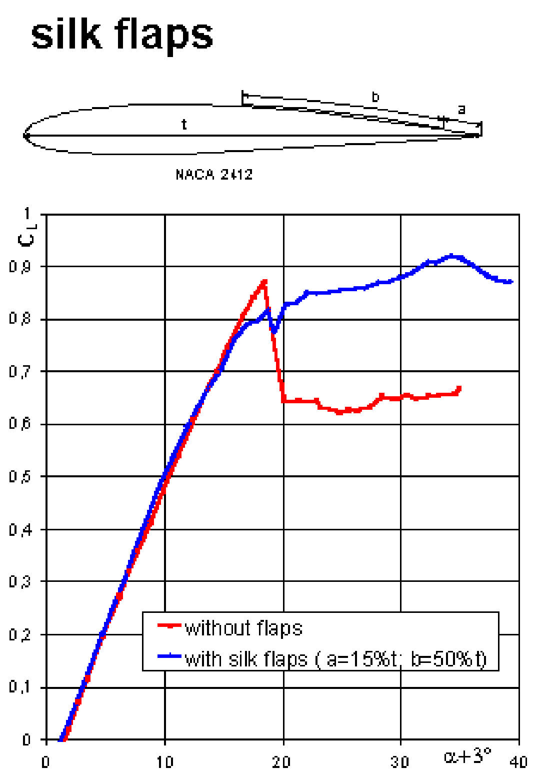
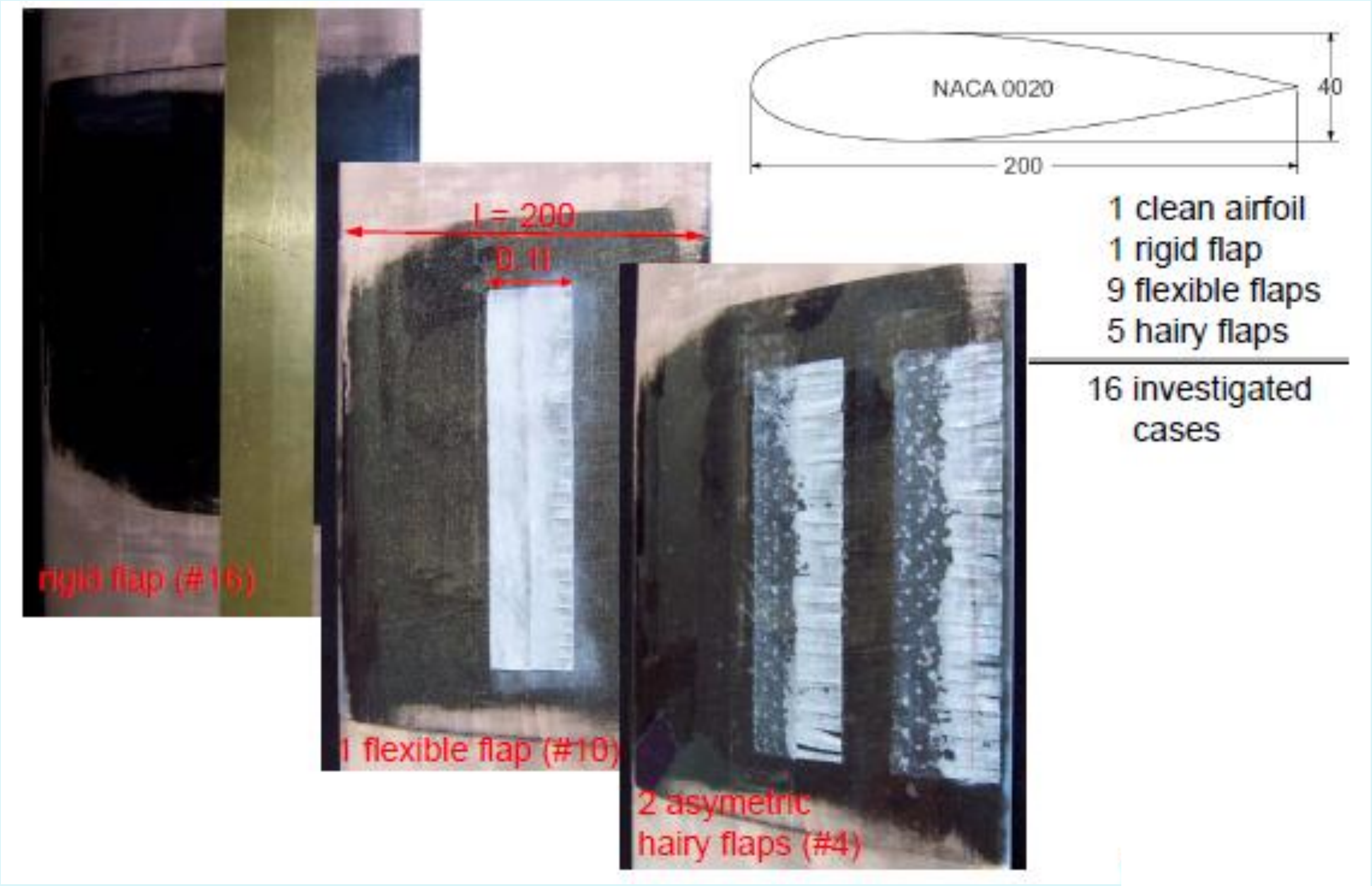
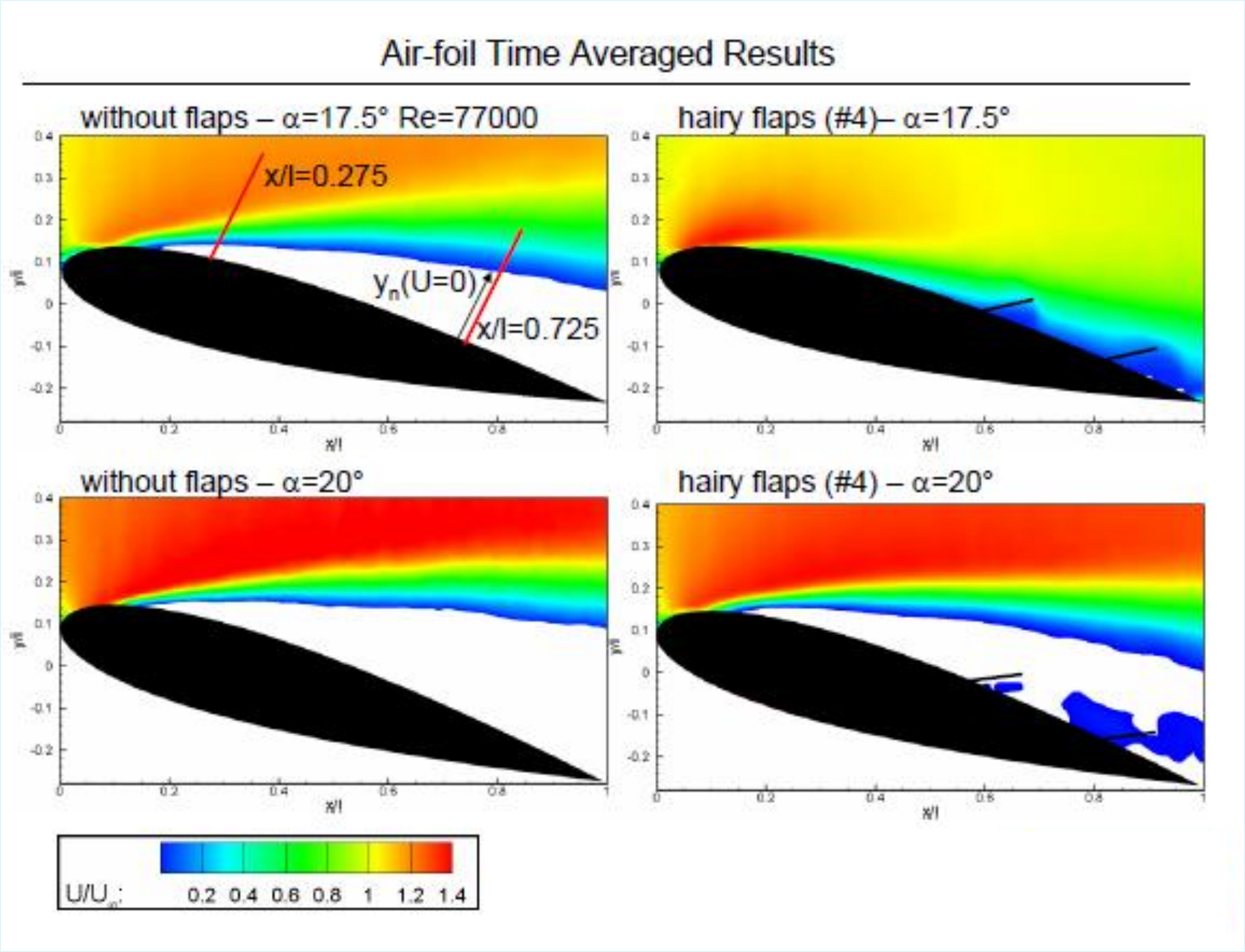



Flexible, porous flaps delay stall …

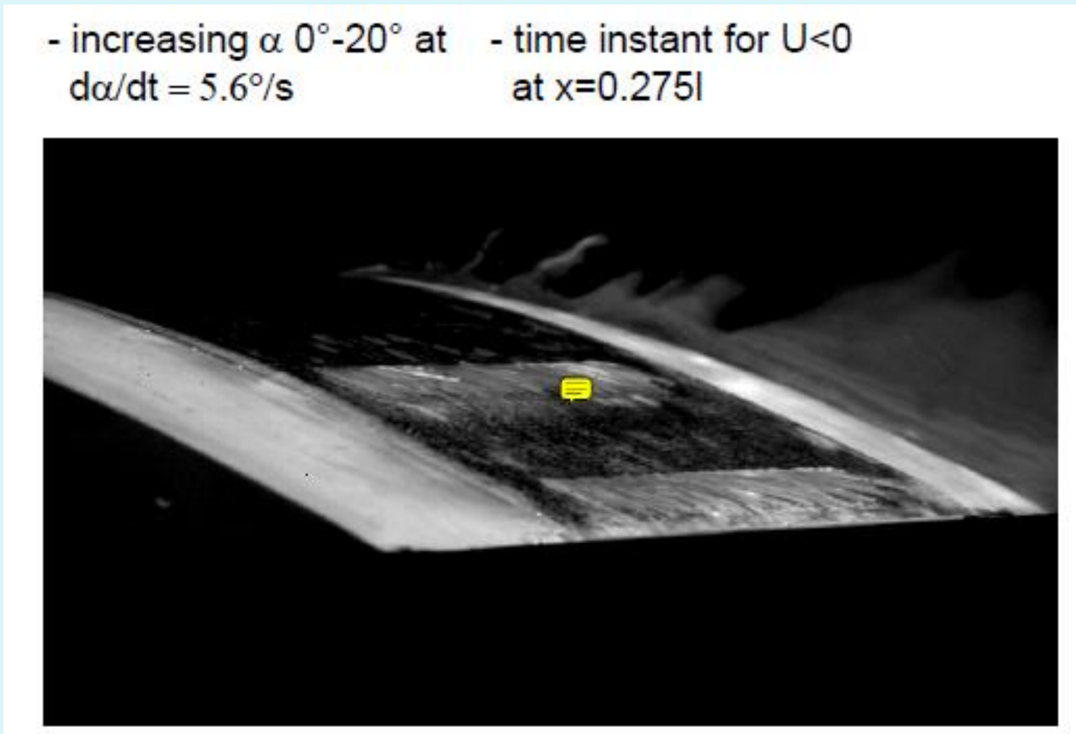
# Experiments (Freiberg)



# Experiments (Freiberg)

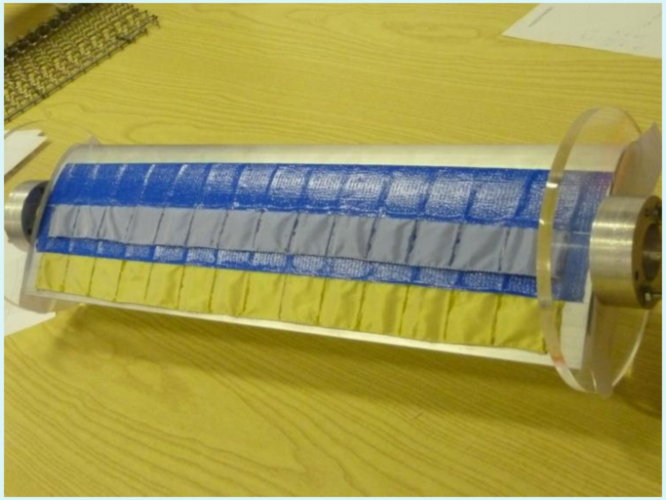


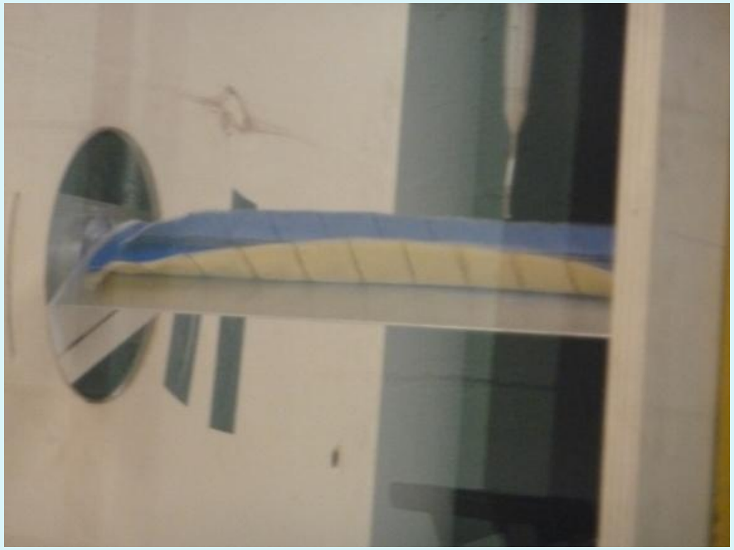
# Experiments (Freiberg)



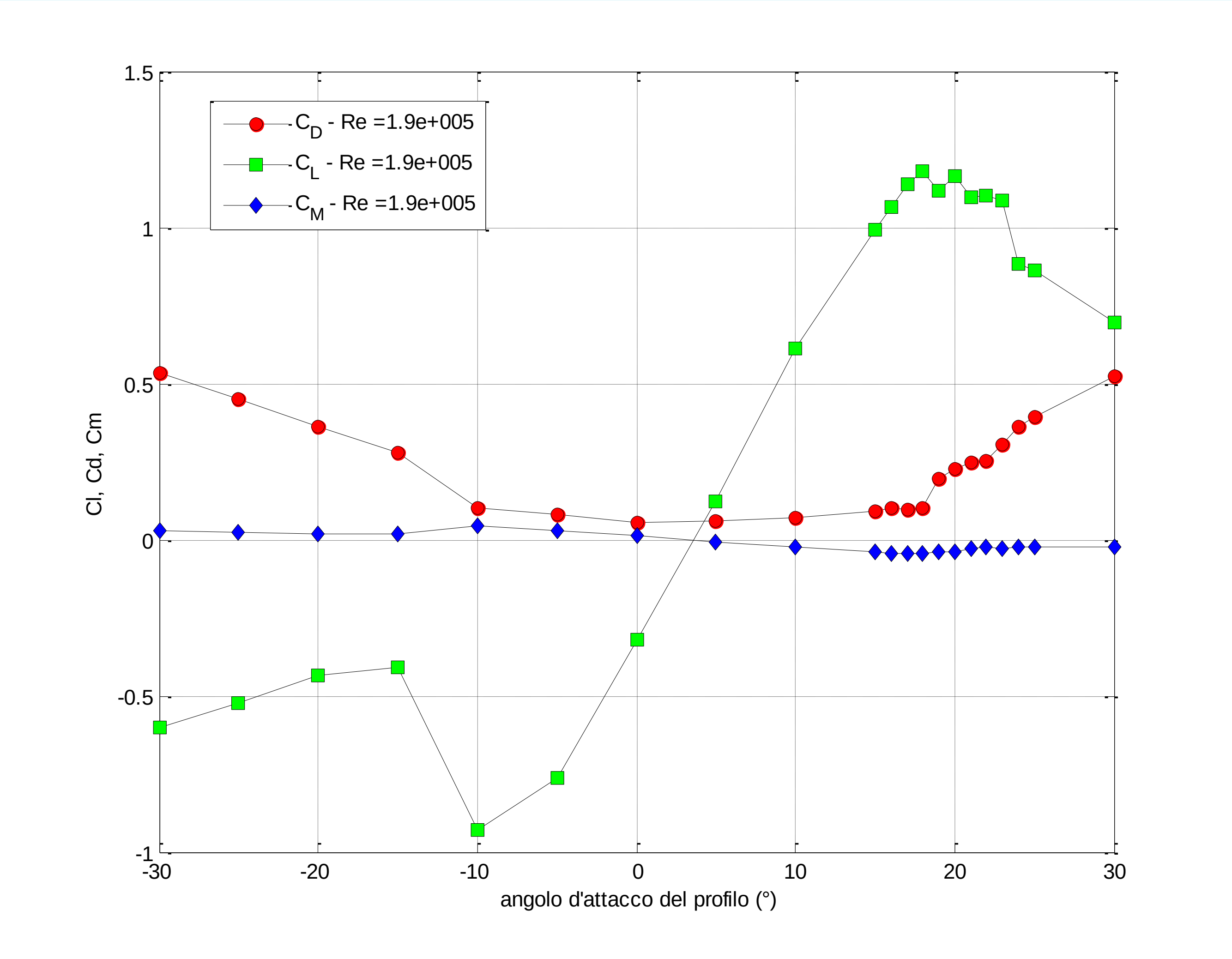

- Flexible and hairy flaps oppose separation at fixed angles of attack
- Hairy flaps delay flow separation in pitching experiments

# Experiments (Genova)

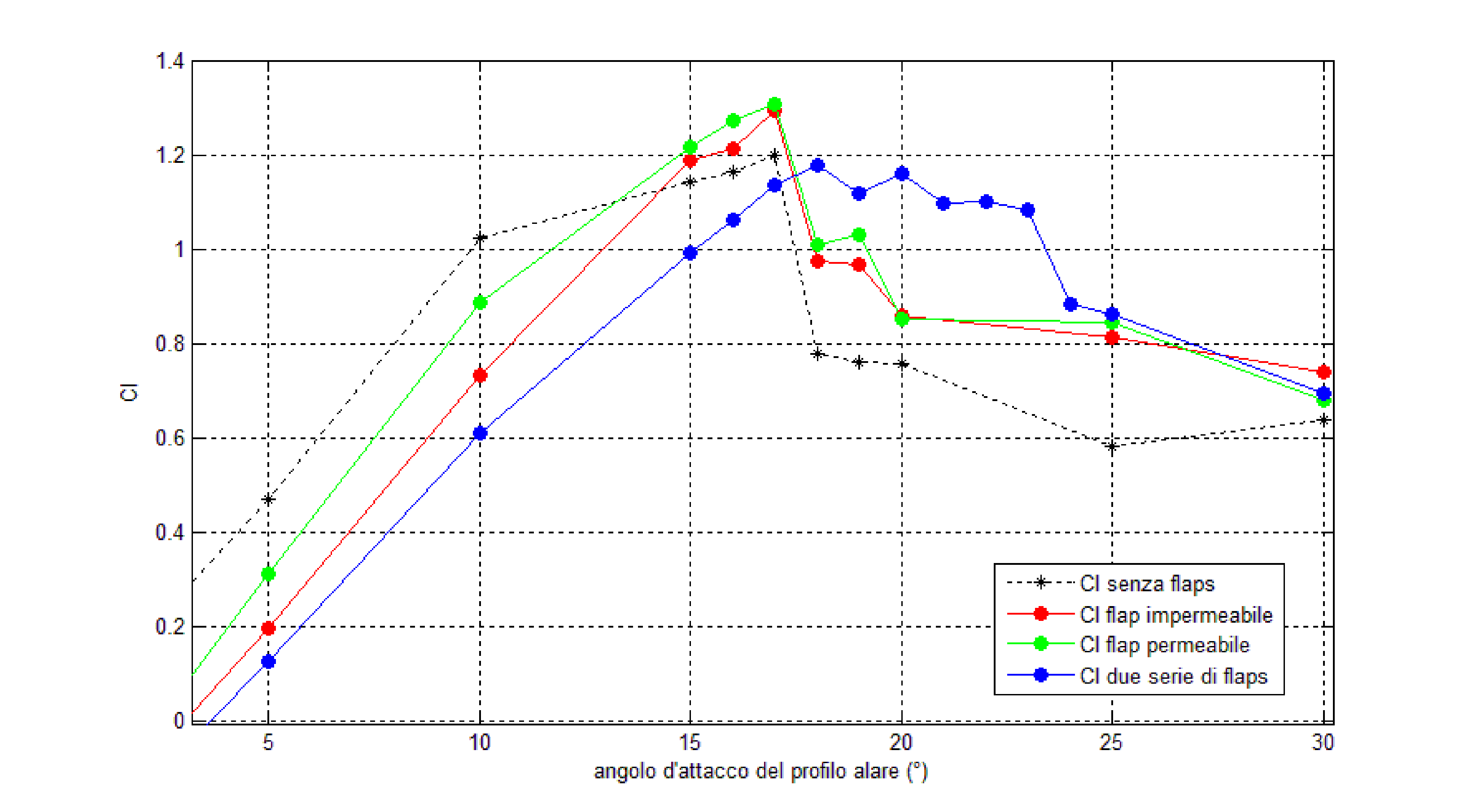




# Experiments (Genova)



# Experiments (Genova)



# Options:

| Experiments | Poroelasticity theory | NS IBM simulations | Low order model |
|---|---|---|---|

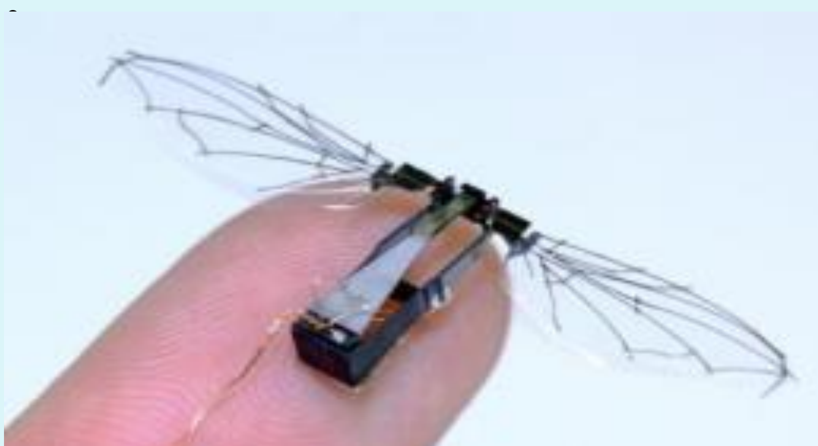
Gopinath & Mahadevan (*Proc. Royal Soc. A*, 2010)

# Options:

| | | | |
|---|---|---|---|
| **Experiments** | **Poroelasticity theory** | **NS IBM simulations** | **Low order model** |

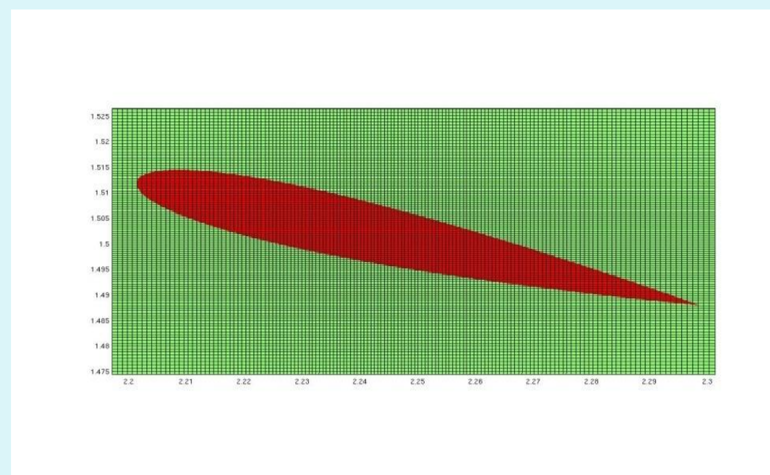
Present work (at low Re number)

- NACA0012 airfoil
- More difficult to control separation of boundary layer in laminar case – boundary layer less capable of handling adverse pressure gradient without separation.
- Low Reynolds number (1100) particularly used for testing performance of MAVs.



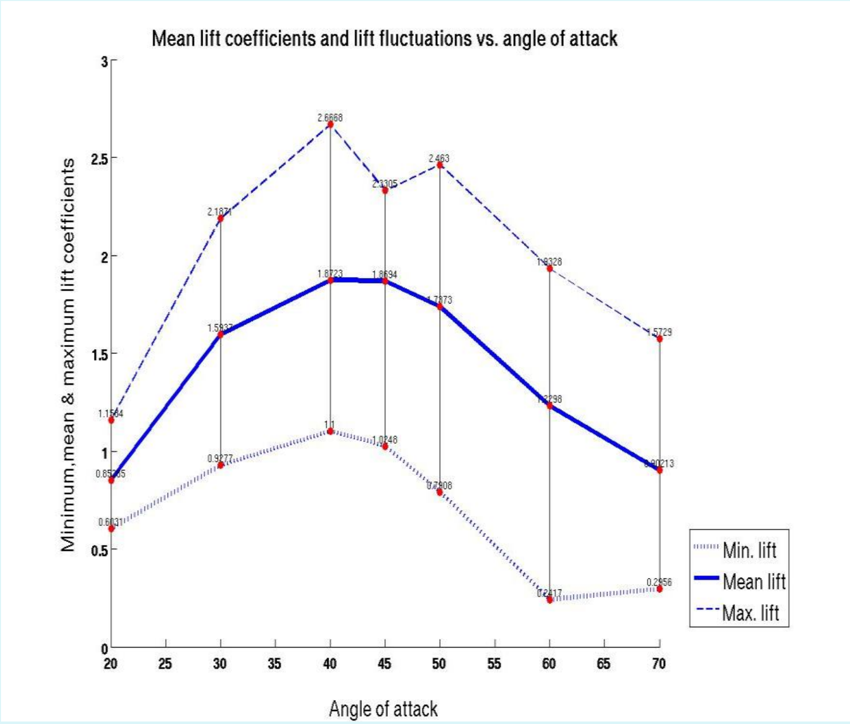
- Incompressible, unsteady 2D N-S eqns. with forcing
- Immersed Boundary Method: Stationary, non-conformal Cartesian grid (fine on and near airfoil)
- Feedback forcing term in N-S: Spring-mass system

$$\boldsymbol{F} = \alpha \int(\mathbf{0} - \mathbf{U})dt + \beta\,(\mathbf{0} - \mathbf{U})$$

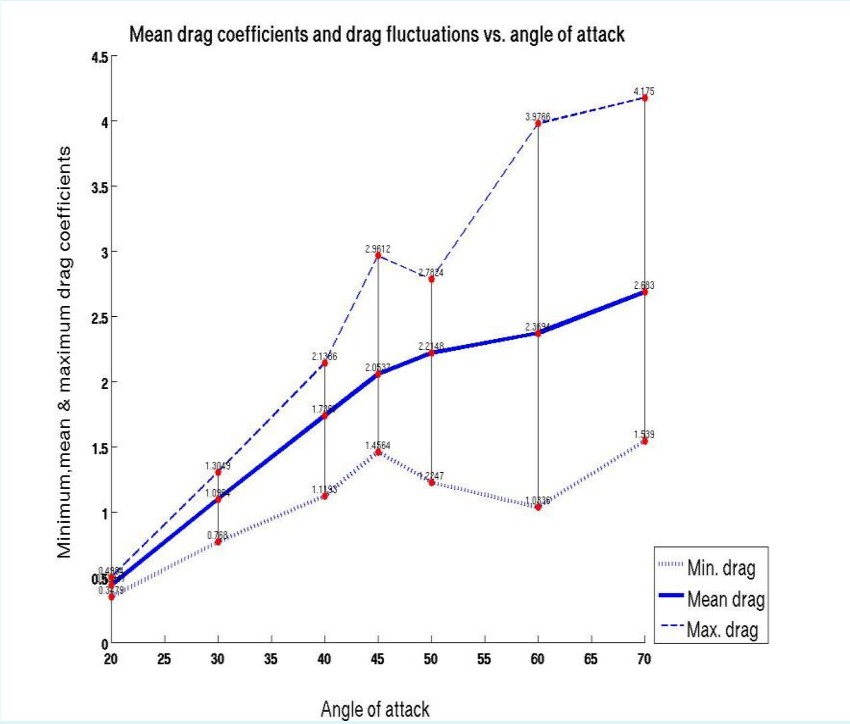


# *RESULTS: NO-CONTROL CASE*

Mean lift as a function of angle of attack (between 20° and 70°) - steady drop in lift after 45°.

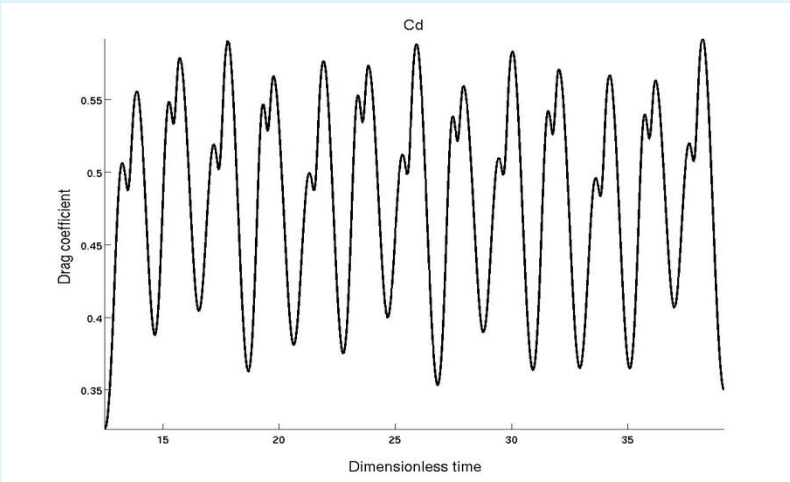


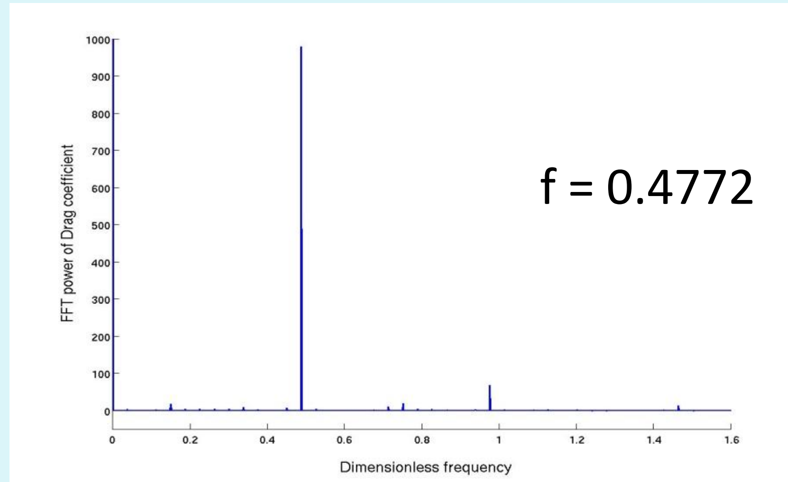

Mean drag as a function of angle of attack (between 20° and 70°).

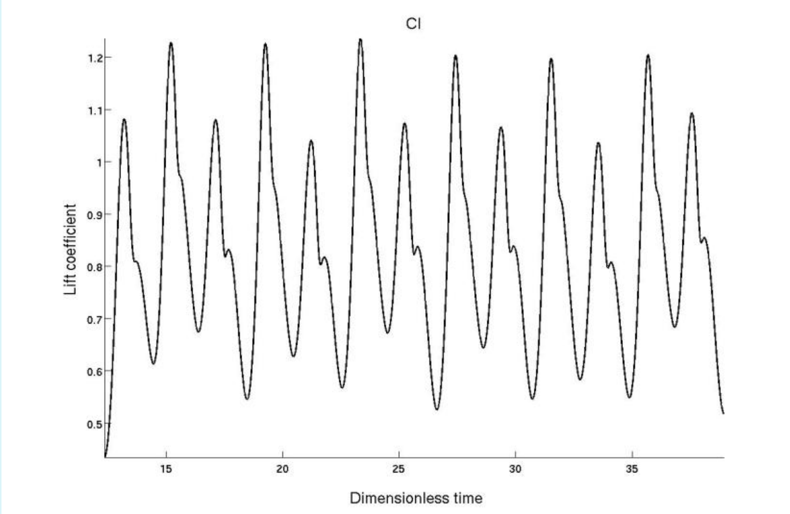


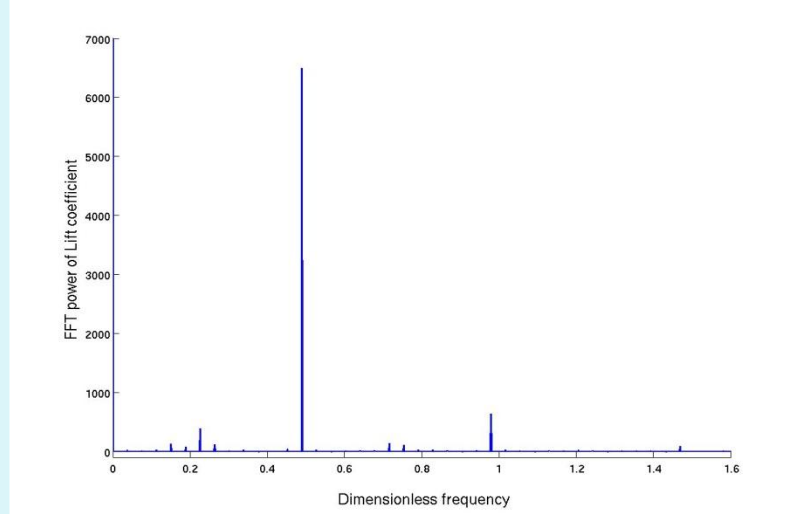

**An effective control should see a correlation between the time scale of the vortex shedding frequency and the natural time scale of the structures**

# Power Spectra of Drag & Lift Signals : 22 degrees

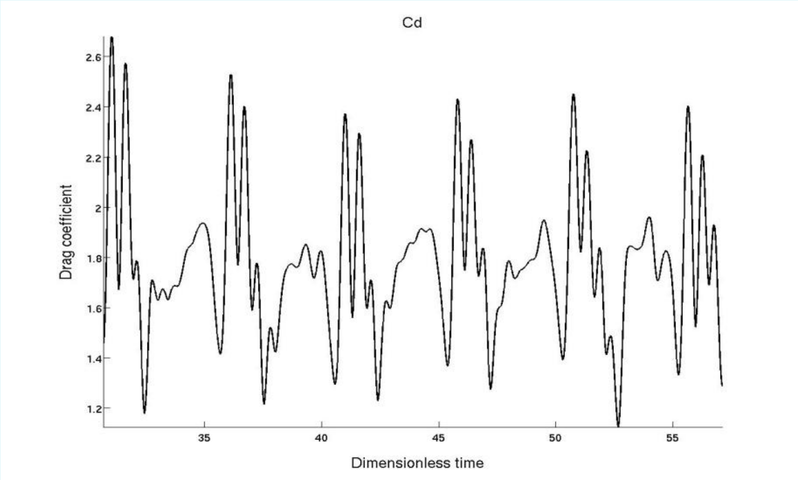


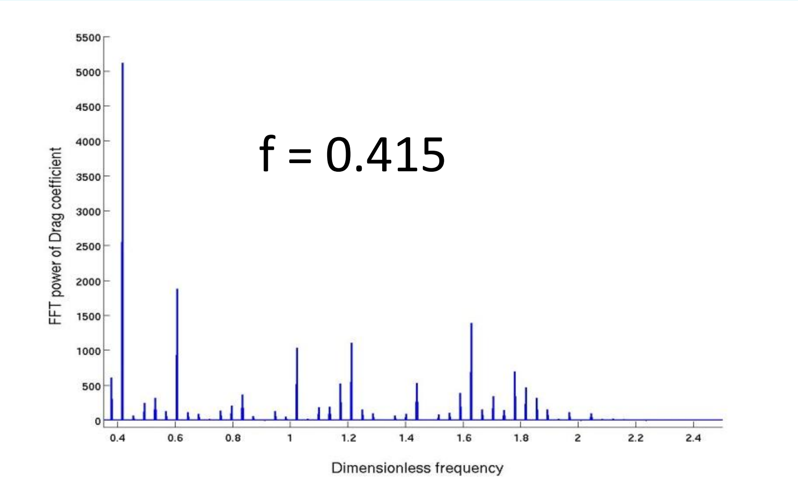



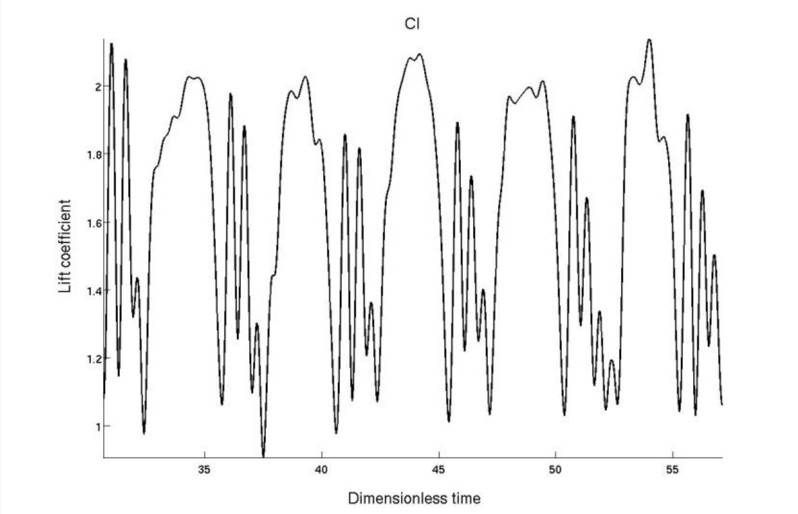



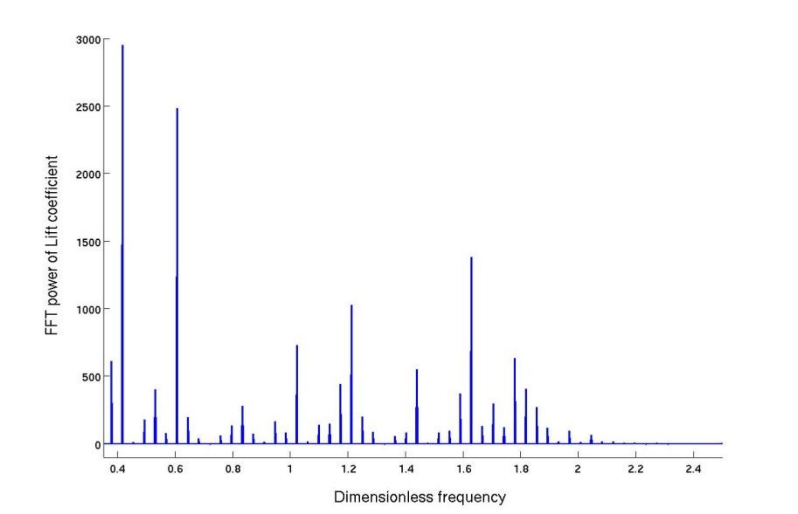



# Power Spectra of Drag & Lift Signals : 45 degrees

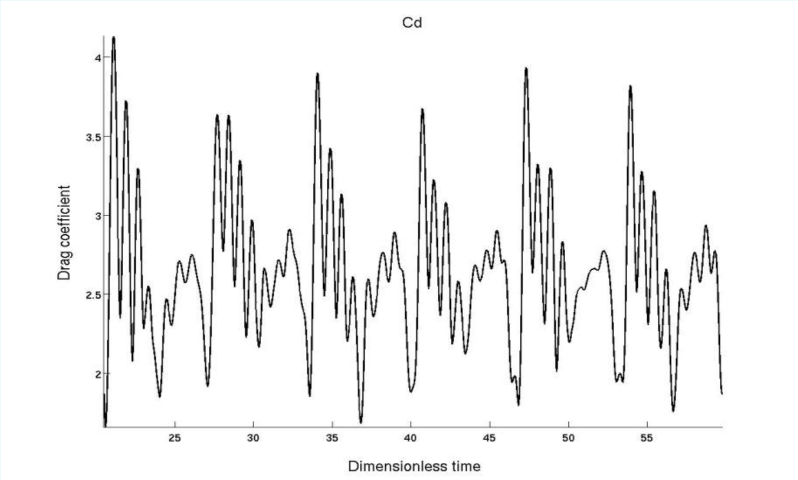


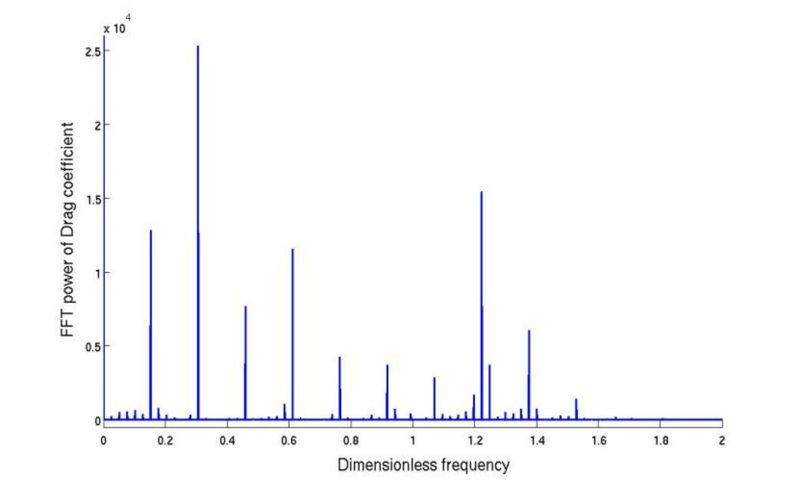



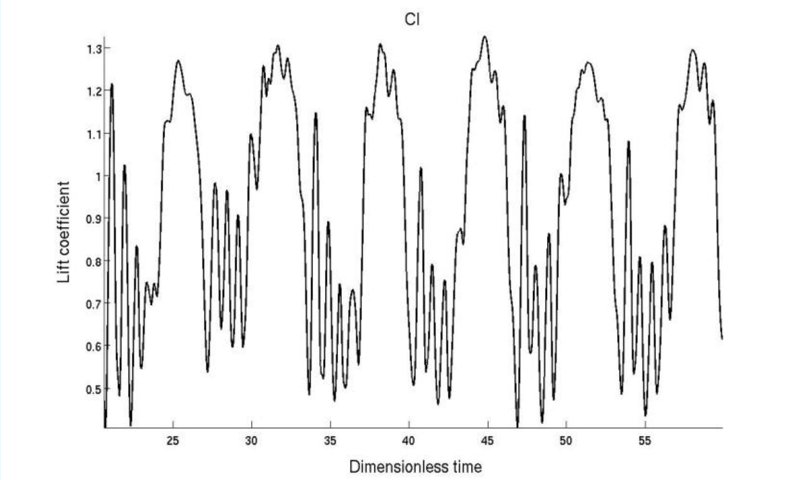



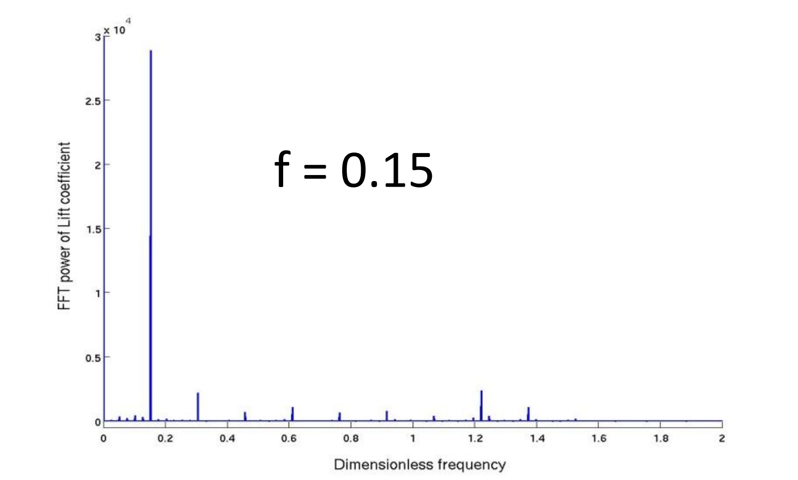



# Power Spectra of Drag & Lift Signals : 70 degrees



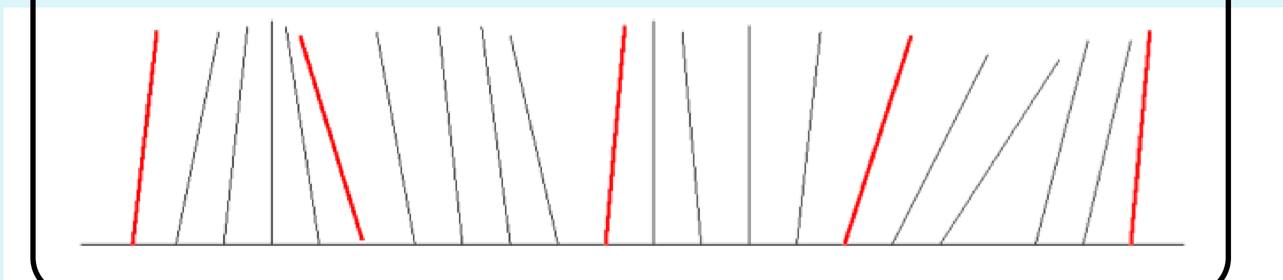
# Modeling in 3 points

Modeling all feathers: too heavy …

→ Must reduce the number of degrees of freedom

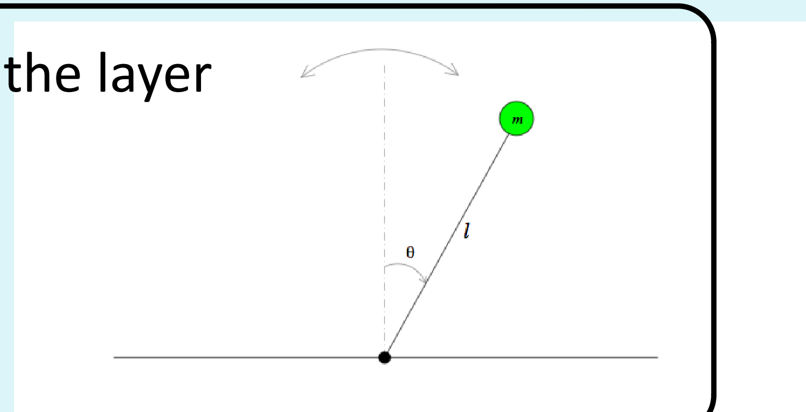
1. **Homogenized approach**: description of the layer in terms of **density** and **direction** of feathers.
2. Motion of the layer reduces to the oscillation of a small number of **reference elements**
3. The fluid “sees” the structures in terms of **volume forces** (and the same for the structures)

## Homogenized approach



## Dynamics of the layer

Approximation :
Rigid **reference** element




*E. De Langre, ARFM, 2008*

# Fluid part...

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla(\mathbf{U}\mathbf{U}) = -\frac{\nabla p}{\rho} + \nu \nabla^2 \mathbf{U} + \mathbf{F}; \ \nabla \cdot \mathbf{U} = 0$$

2D incompressible
Volume forces formulation

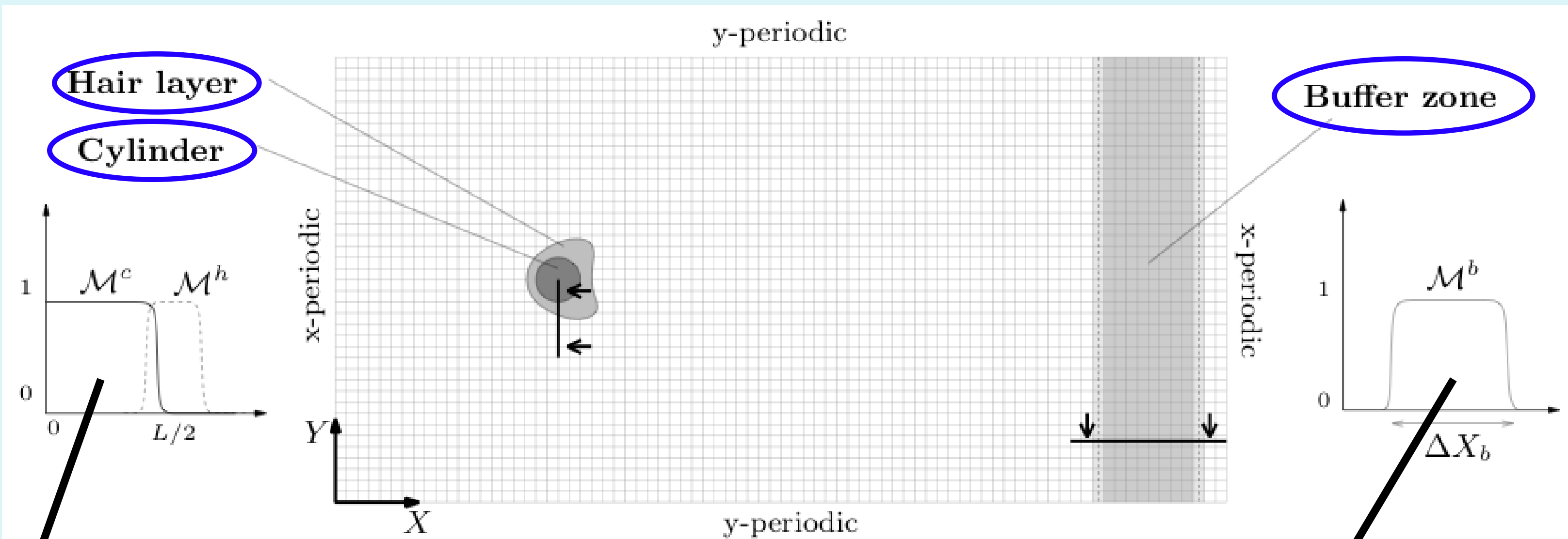
Staggered grid
Periodic boundary conditions,
with buffer domain to treat I/O

Convective part: Adams-Bashfort
Viscous part: Crank-Nicolson
Poisson and implicit parts solved using conjugate gradient

→ order 2 in space and time

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla(\mathbf{U}\mathbf{U}) = -\frac{\nabla p}{\rho} + \nu \nabla^2 \mathbf{U} + \mathbf{F} \,; \; \nabla \cdot \mathbf{U} = 0$$

Regular cartesian mesh 200 x 400 (10L x 20L)



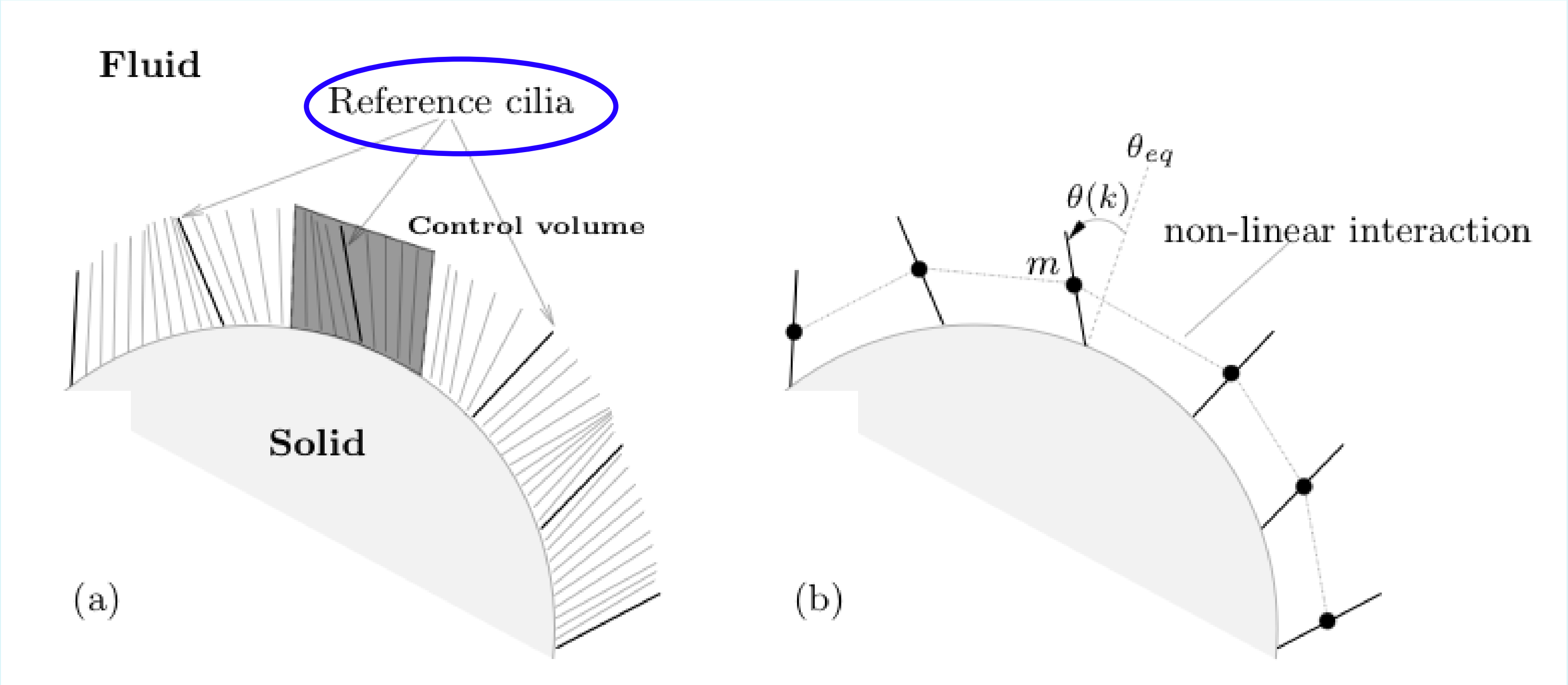

$$\mathbf{F}^c = \mathcal{M}^c \left( \alpha^c \int_{t_0}^{t} (\mathbf{0} - \mathbf{U})\, dt + \beta^c (\mathbf{0} - \mathbf{U}) \right)$$

$$\mathbf{F}^b = \mathcal{M}^b \left( \alpha^b \int_{t_0}^{t} (\mathbf{U}_\infty - \mathbf{U})\, dt + \beta^b (\mathbf{U}_\infty - \mathbf{U}) \right)$$

$$\mathbf{F} = \mathbf{F}^c + \mathbf{F}^b + \mathbf{F}^h$$

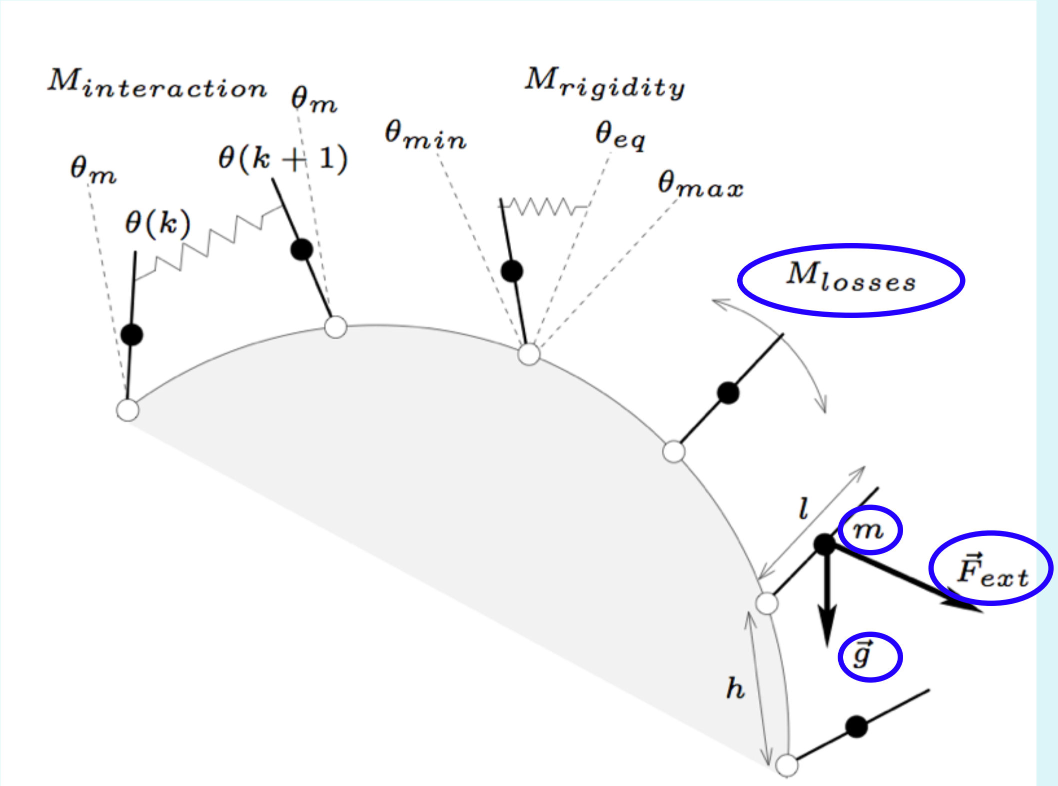
# Structure part ...

"skeleton" of
the layer




→ The dynamics of the layer is governed by the reference elements

→ The “skeleton” of the layer is governed by six terms in the angular momentum equation for each element

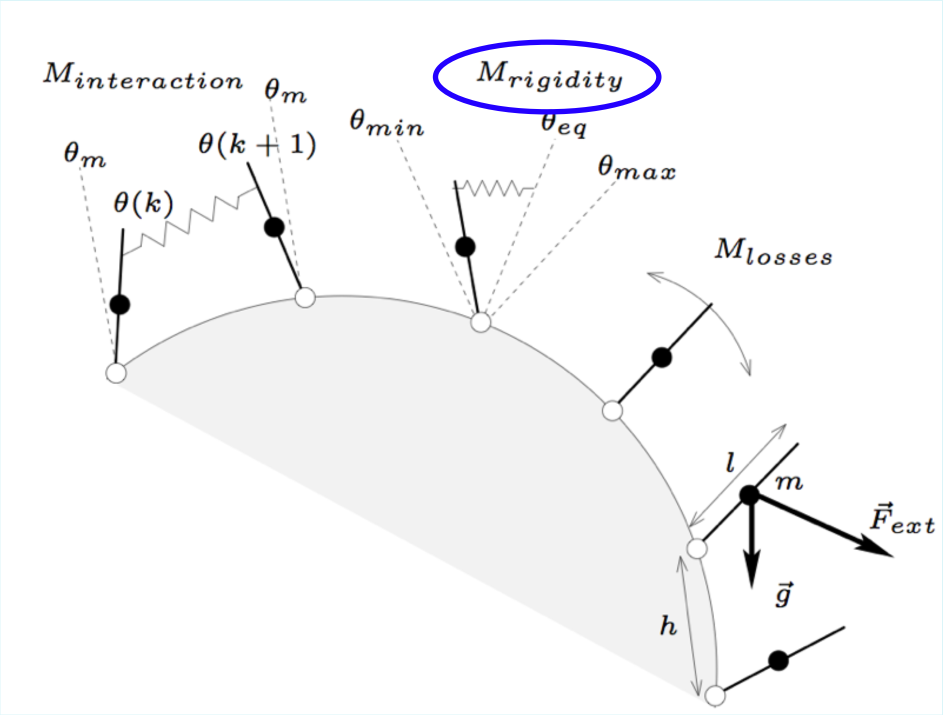


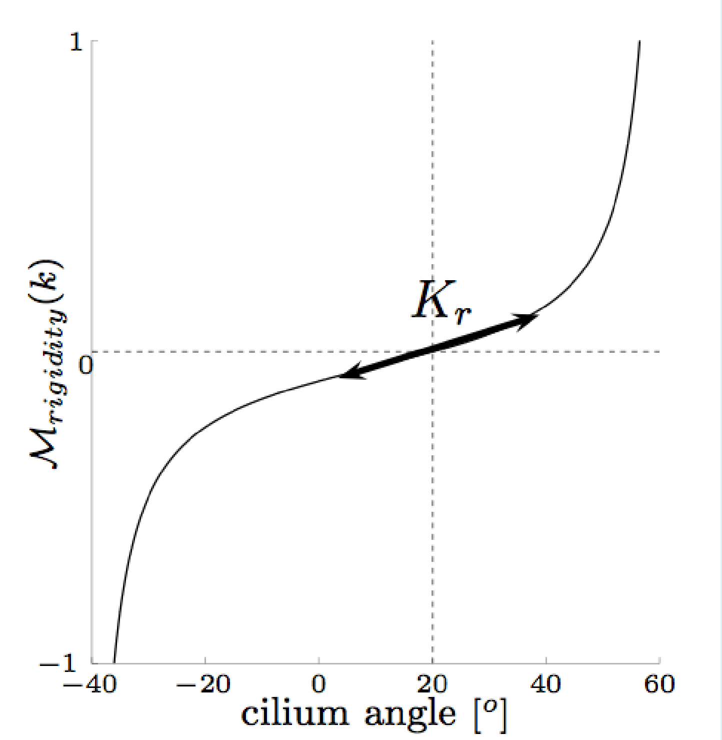

$$M_{losses}(k) = -K_l\,\dot{\theta}(k)$$

$$M_{inertia}(k) = -m\frac{l^2}{4}\ddot{\theta}(k)$$

$$M_{gravity} = mg\tfrac{l}{2}\sin(\theta)$$

$$M_{ext}(k) = \frac{l}{2}F_n(k)$$



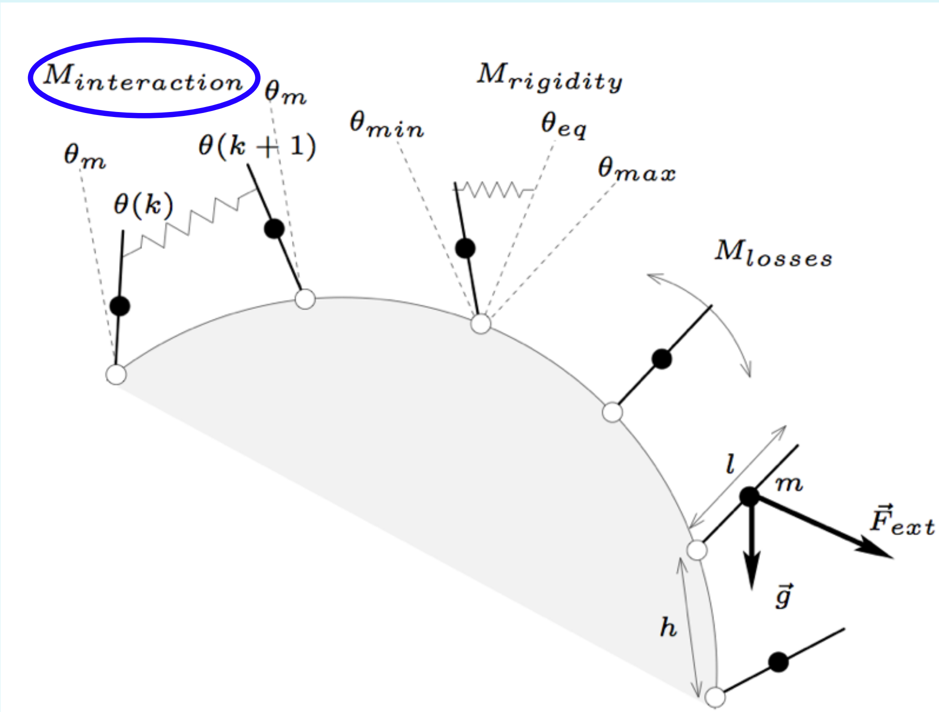



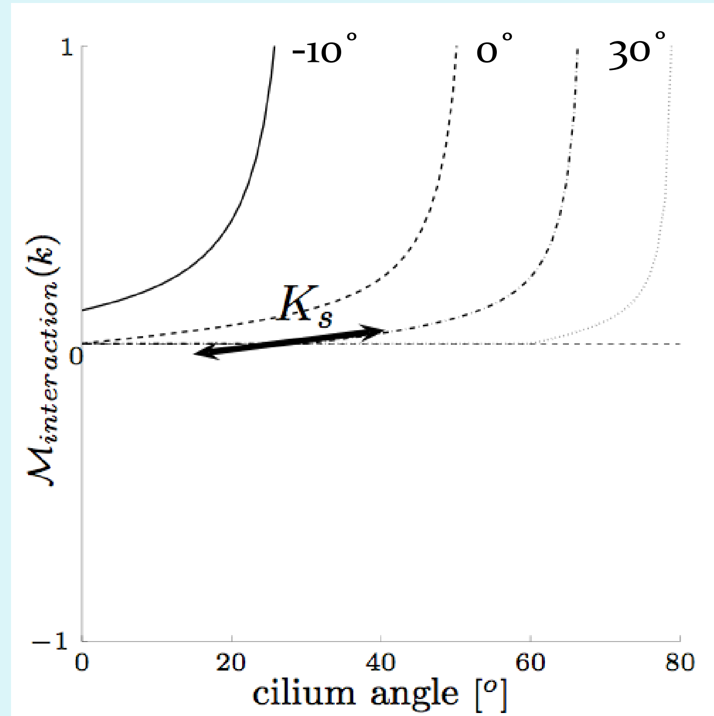

$$M_{rigidity}(k) = -K_r \frac{P(\theta) - P(\theta_{eq})}{P'(\theta_{eq})}$$

avec $P = \tan(a\theta + b)$

$$a = \pi / (\theta_{max} - \theta_{min})$$

$$b = -a(\theta_{max} + \theta_{min})/2$$




$$M_{interaction}(k) = K_s \tanh \frac{2l \sin(\theta(k) - \theta_m)}{h \cos(\theta_m)}$$

avec $\theta_m = \dfrac{\theta(k) + \theta(k+1)}{2}$

## Explicit (Runge-Kutta 4) and implicit (nonlinear conjugate gradient) resolution of the angular momentum balance of each reference fiber

$$m(l/2)^2\ddot{\theta}(k) = M_{spring}(k) + M_{rigidity}(k) + M_{dissip}(k) + M_{inertia}(k) + M_{ext}(k)\ ,\ k = 1, \ldots, N_c$$

Equilibrium is reached after a sufficient number of sub-iterations

How to evaluate the force imposed by the fluid onto the structures ...

# How to evaluate the force imposed by the fluid onto the structures ...

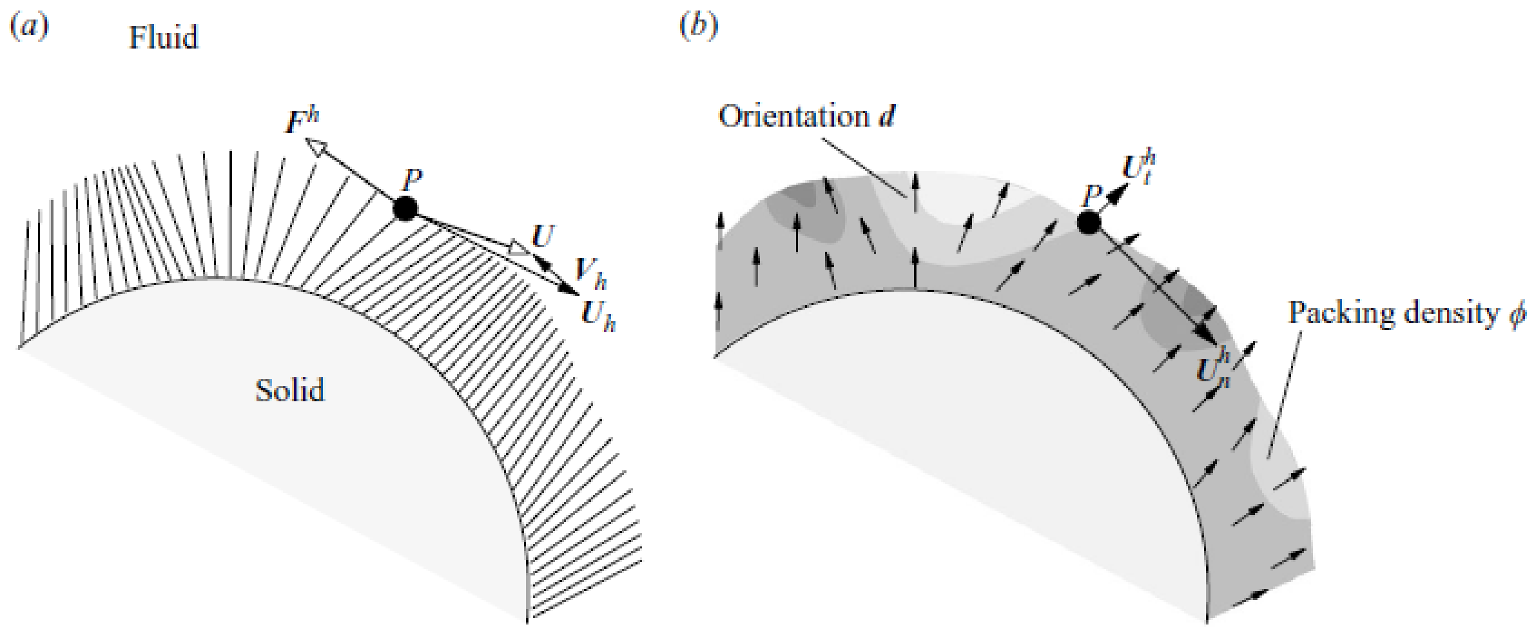
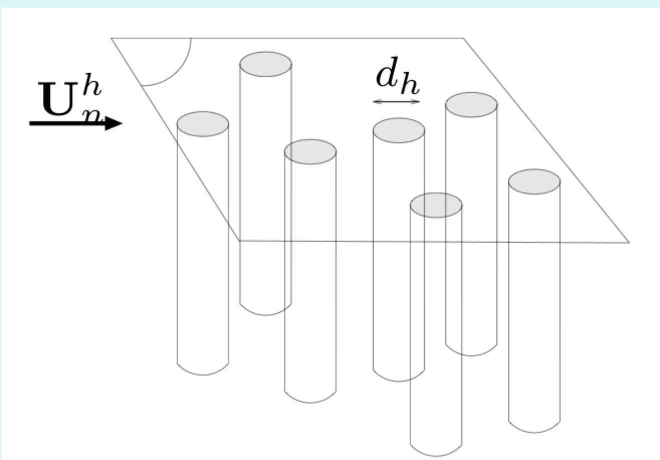



FIGURE 5. Homogenized model of the furry coating and sketch of the volume force $F^h$ imposed on the fluid. ($a$) Hairy layer covering a cylinder and relative fluid velocity $U^h$ at any point $P$ of the layer, while the single element moves at velocity $V^h$. ($b$) Gray scale of the packing density $\phi$ and vector $d$ orientation of the elements within the hairy layer. At point $P$, tangential and normal velocity components used to estimate the two components of $F^h$ are displayed.

# Homogenized part (fluid+structure) ...

- Each cilium is a circular cylinder
- At each point along the beam, the force is decomposed into a tangential and a normal contribution
- Force on a random cluster of cylinders

## Estimate of $F_n$




$$\frac{||\mathbf{F}_n^h||}{\mu||\mathbf{U}_n^h||} = c_0(\phi) + c_1(\phi)Re_n^h$$

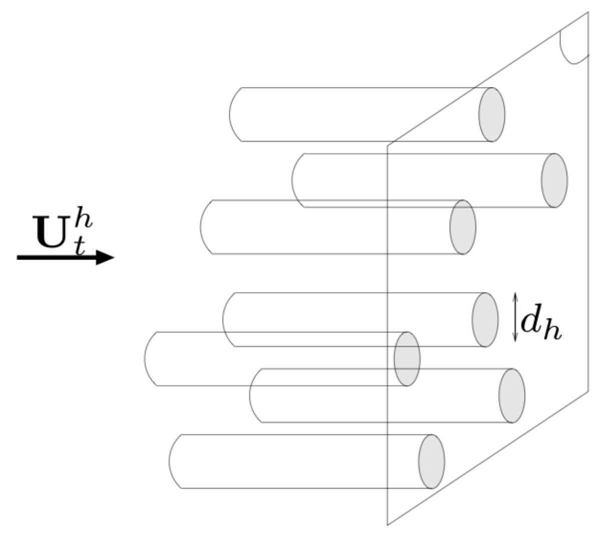
theoretical (Re=0)   empirical Re<180

*Koch & Ladd, JFM 1997*

$$||\mathbf{F}_n^h|| = f_2(\phi, Re_n^h)$$

# Homogenized part (fluid+structure) ...

## Estimate of $F_t$




→ For Re = 0: Stokes approximation:

$$\frac{\mathcal{F}_t^h}{\mu||\mathbf{U}_t^h||} = \frac{8\pi(1-\phi)^2}{\phi - 1 + \frac{2}{\phi - 1}\ln\phi - 2}$$

$\mathbf{U}_t^h(1-\phi)$ : local velocity through the pores

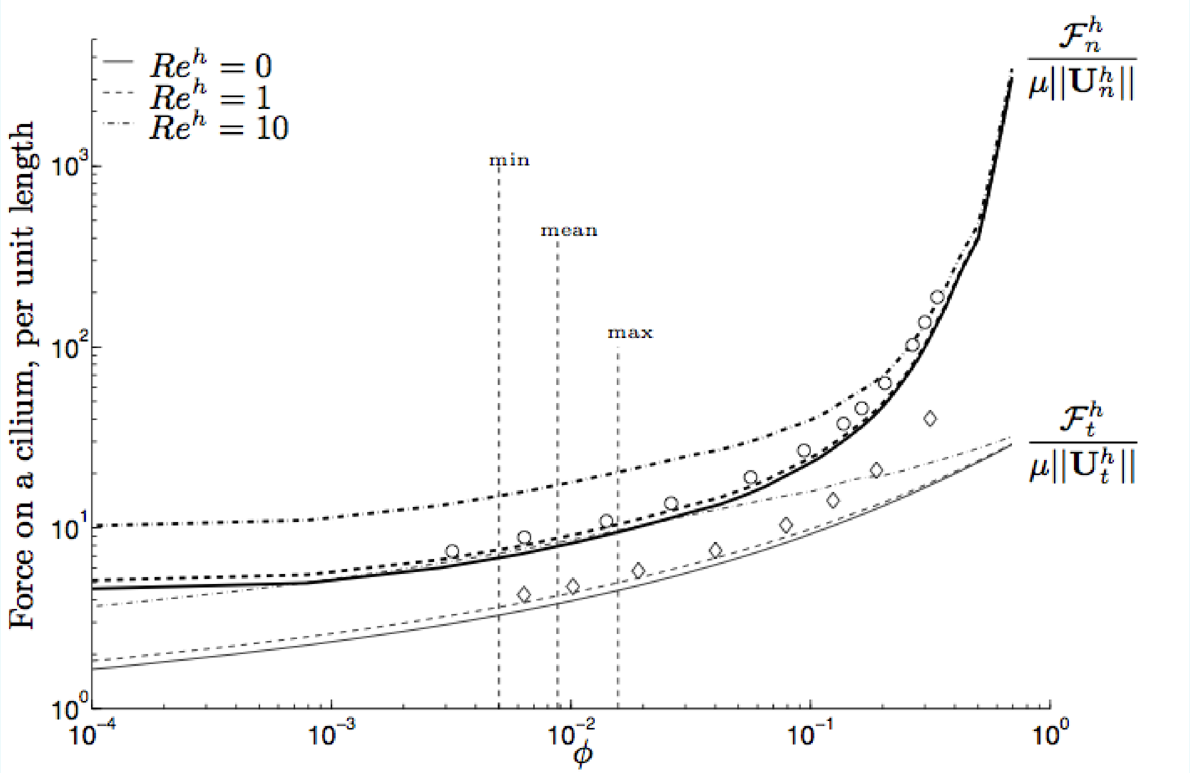
→ For Re<180: same scaling in Reynolds as for $F_n$

$$||\mathbf{F}_t^h|| = f_1(\phi, Re_t^h)$$

# Inner constants of the layer:

Density (nb/cm2),

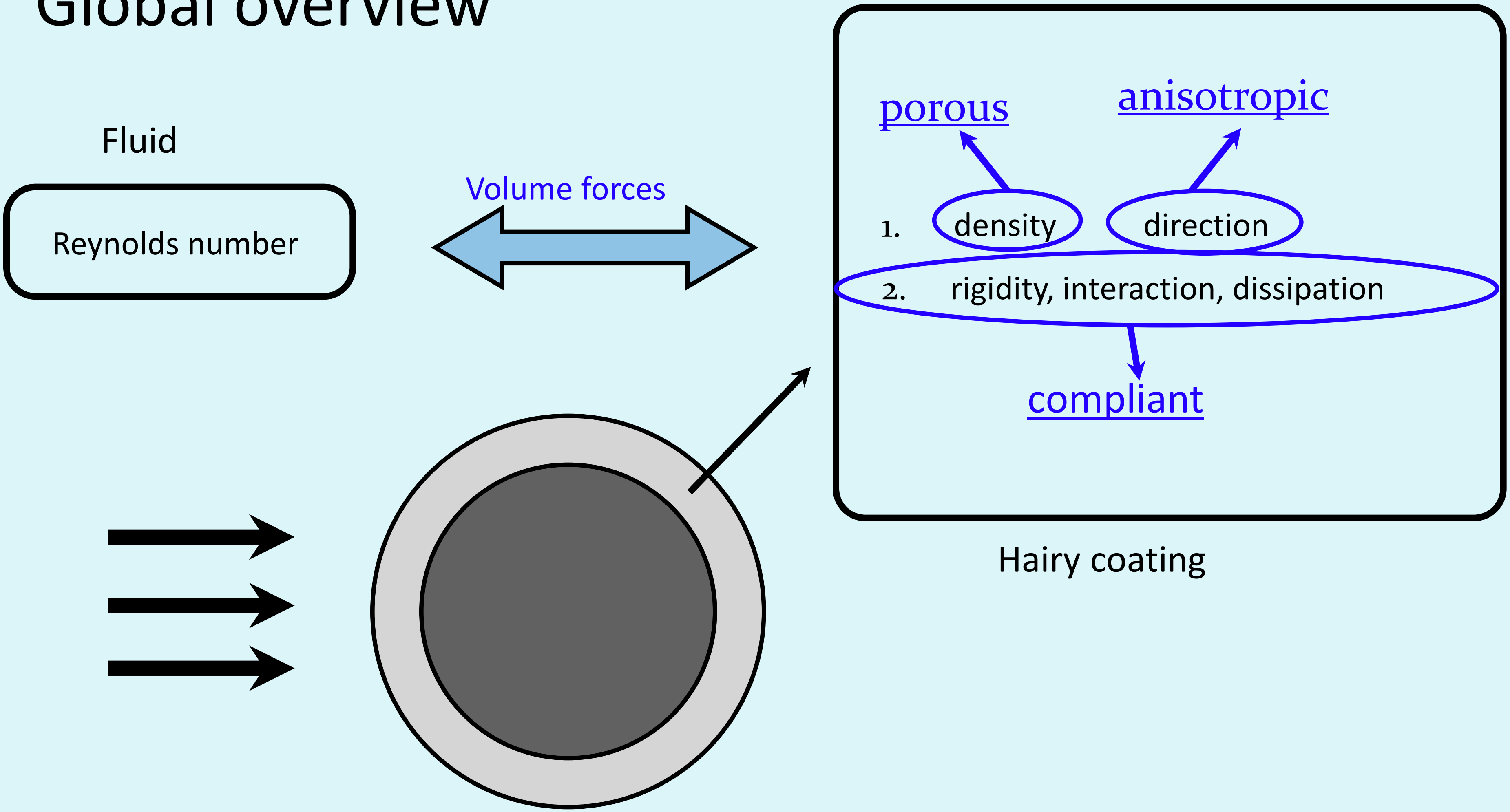
Diameter of cilia




Symbols :
theoretical model by
*Howells, JFM 1998*

$$F_{ext}(k) = \int_{V_{control}(k)} \left\| \boldsymbol{F}^h \right\| \mathrm{d}V$$

# Global overview

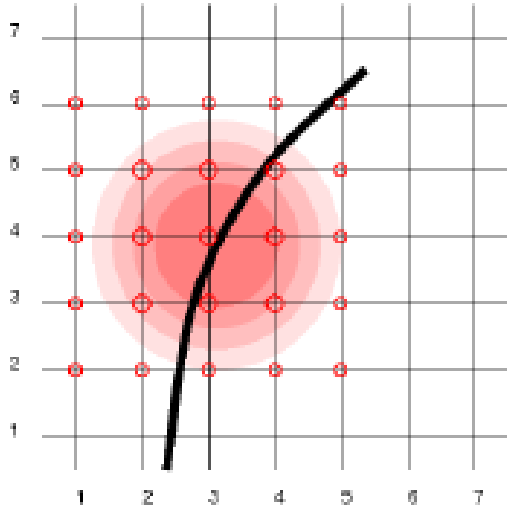


# Volume force of each bristle onto the fluid

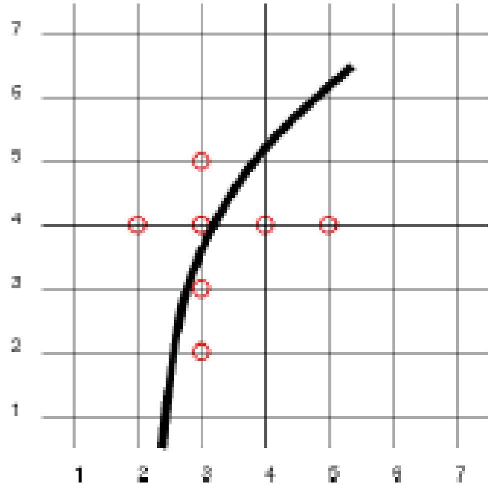
- The DNS is performed on a cartesian mesh. The cilia do not exactly coincide with the nodes → we need to interpolate.

*Two interpolation strategies are tested and compared on two test cases:*

- *Distributed interpolation:*

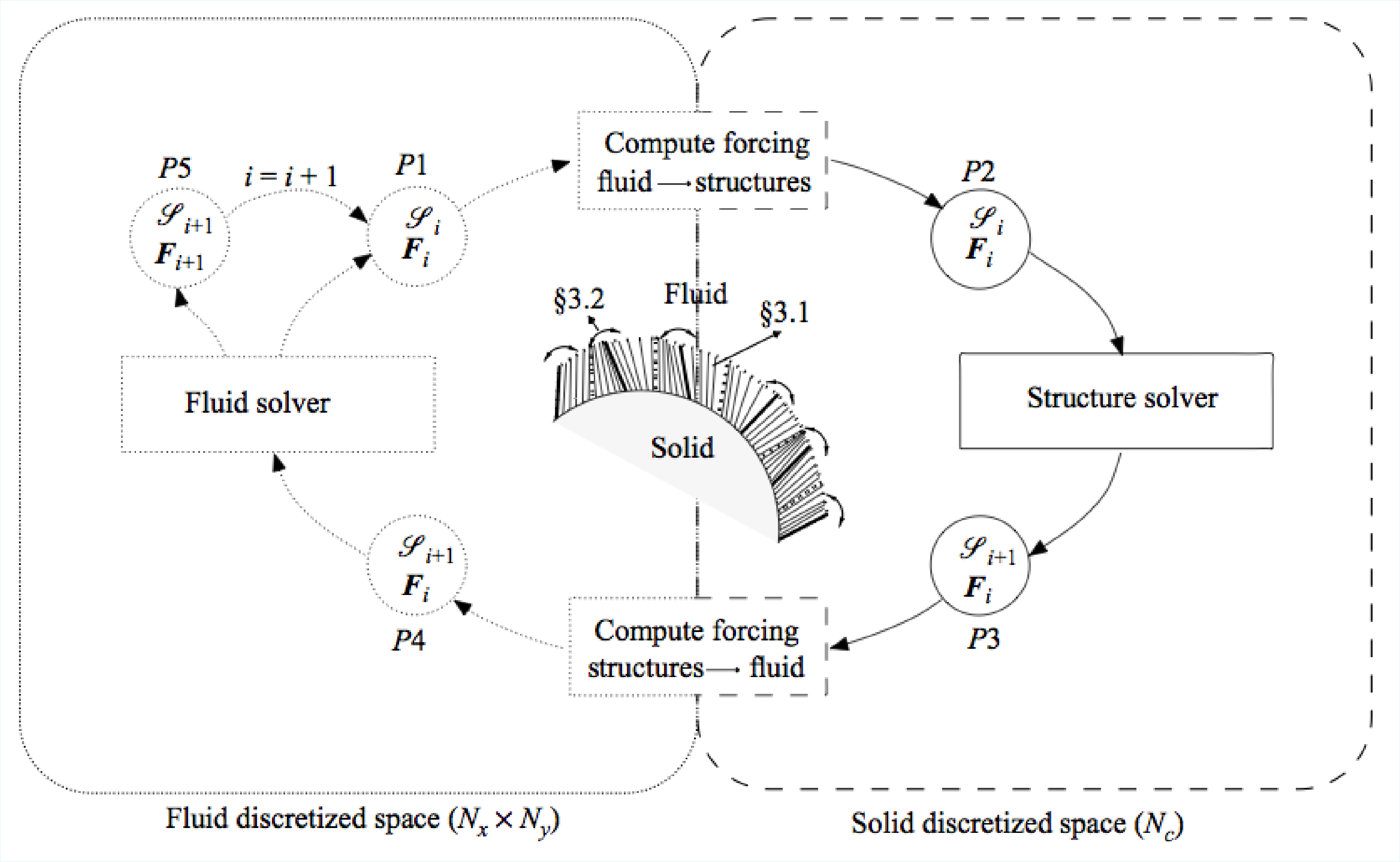


- *Linear interpolation:*

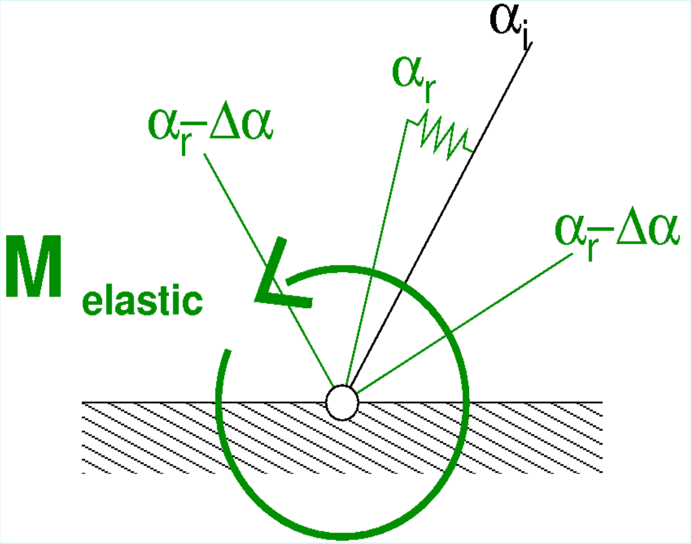


Dauptain *et al.*, JFS 2008

# Weak coupling FSI algorithm



In the structural model, the rigidity/elastic term, which models the structural flexibility of the hairy layer, is the most significant. It defines a natural time scale of the layer, through which a coupling with the fluid is allowed

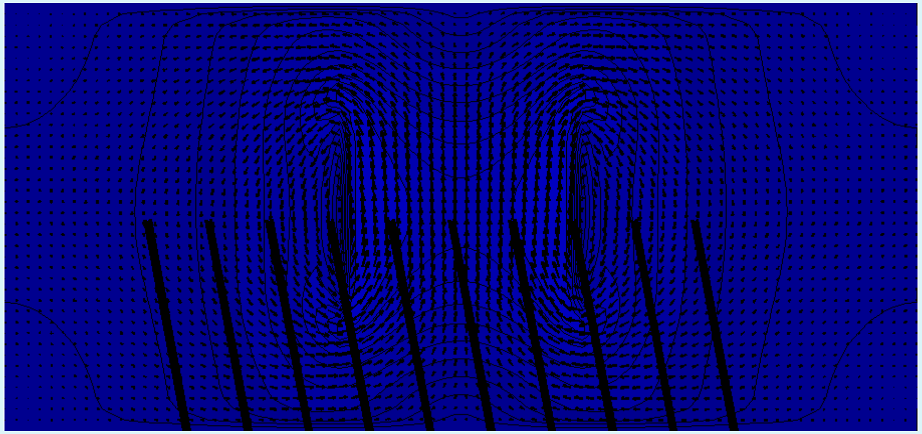


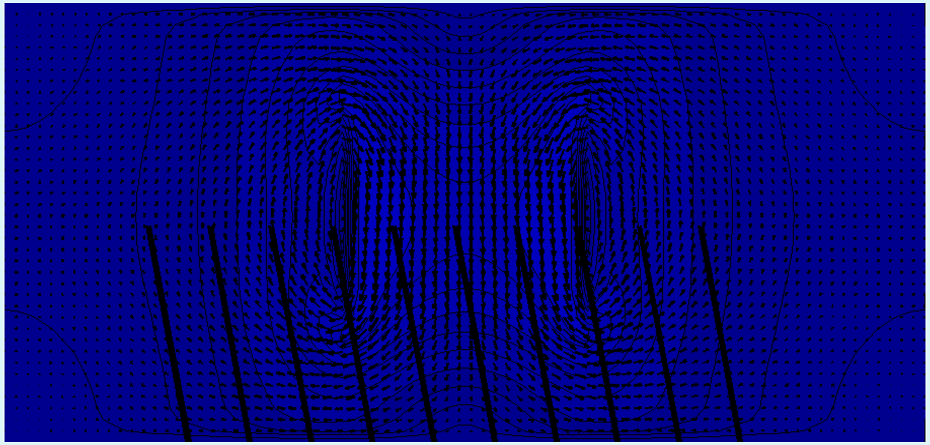

$$T_{structure} \approx \pi\, l\ \sqrt{(m/K_r)}$$

$$T_{fluid} \approx St^{-1}\ D/U_\infty$$

## *Testing the model in the fluid (a vortex pair in a periodic box)*

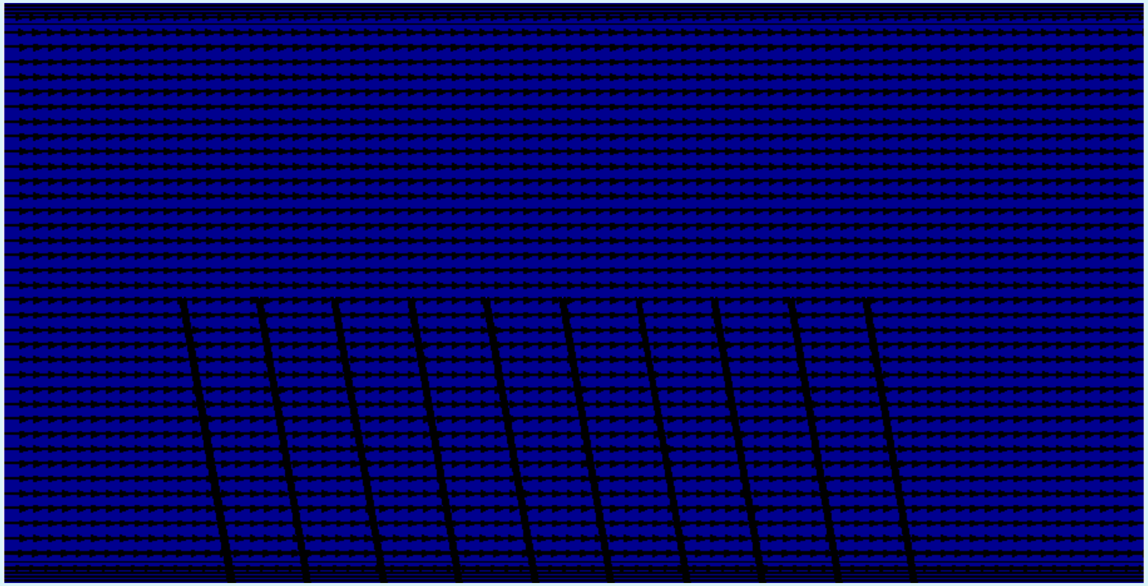
Amplitude of the velocity





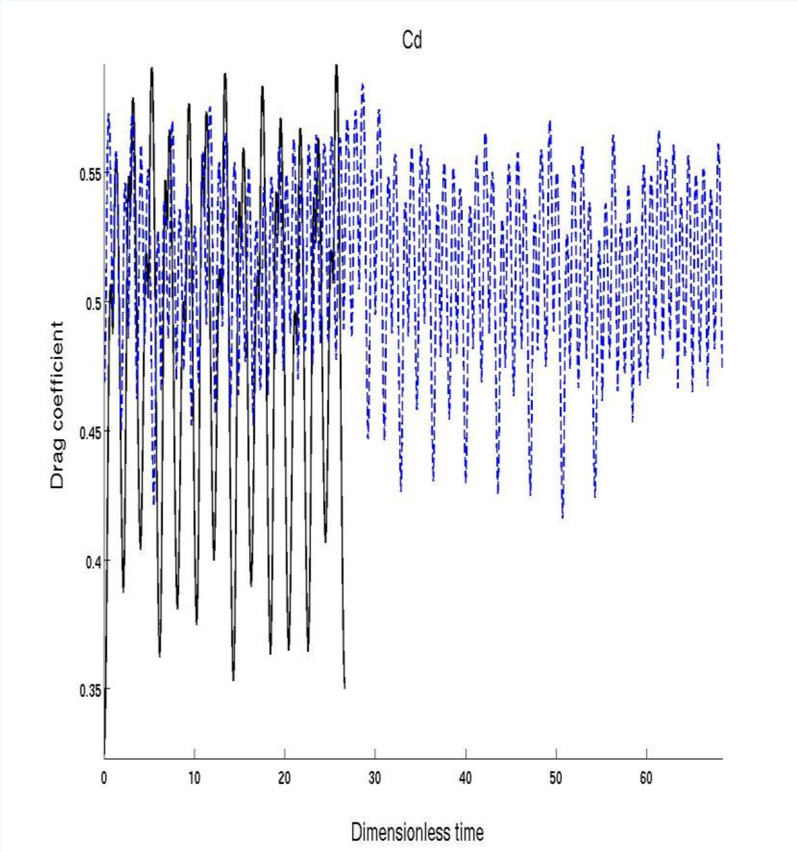
## *Testing the model in the fluid (flow in a channel with one hairy wall)*

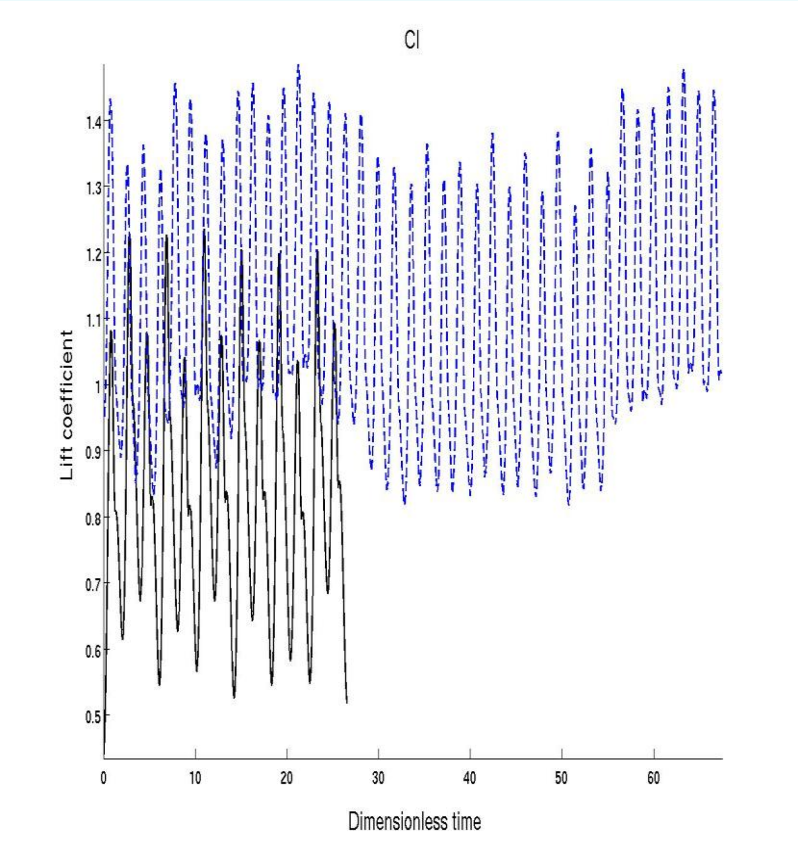
Amplitude of the velocity



*Back to the airfoil with control elements*

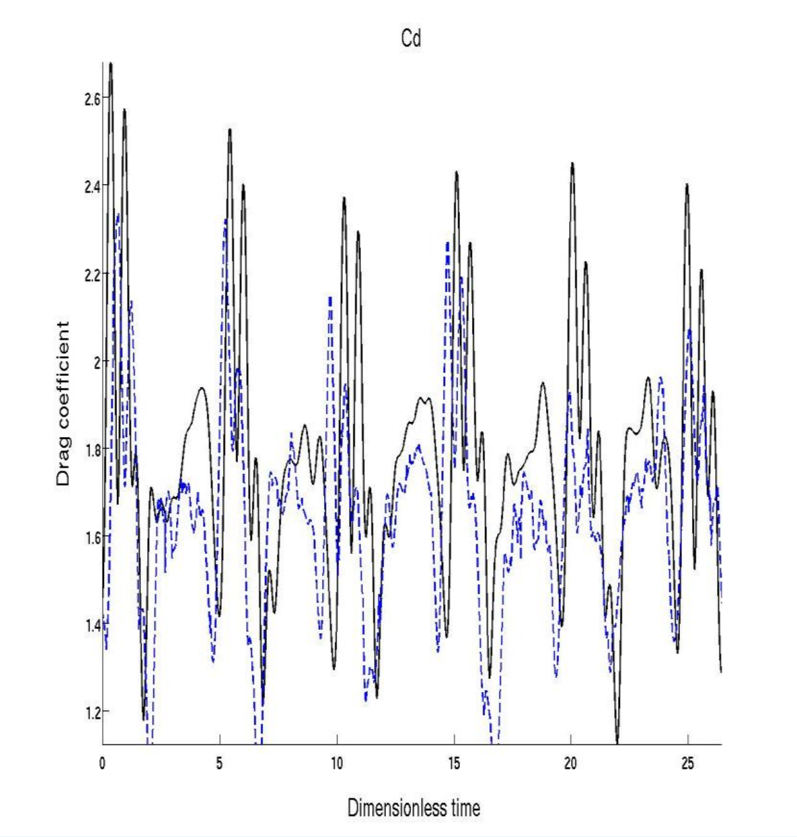
# Comparative Analysis of Drag & Lift – 22 degrees

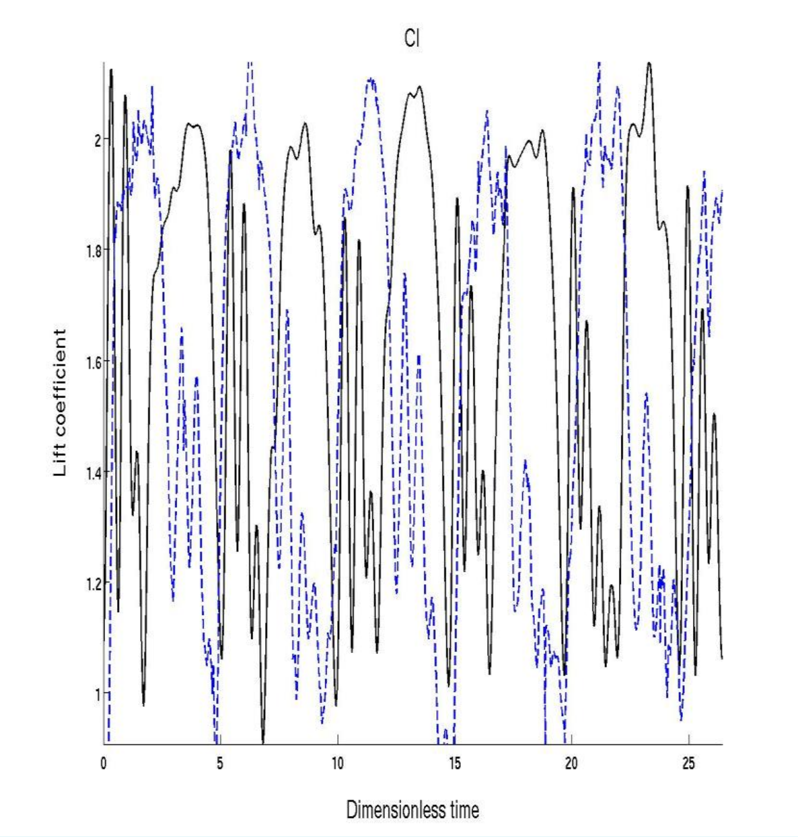



Exact synchronization of fluid shedding time scale and bristles' time scale

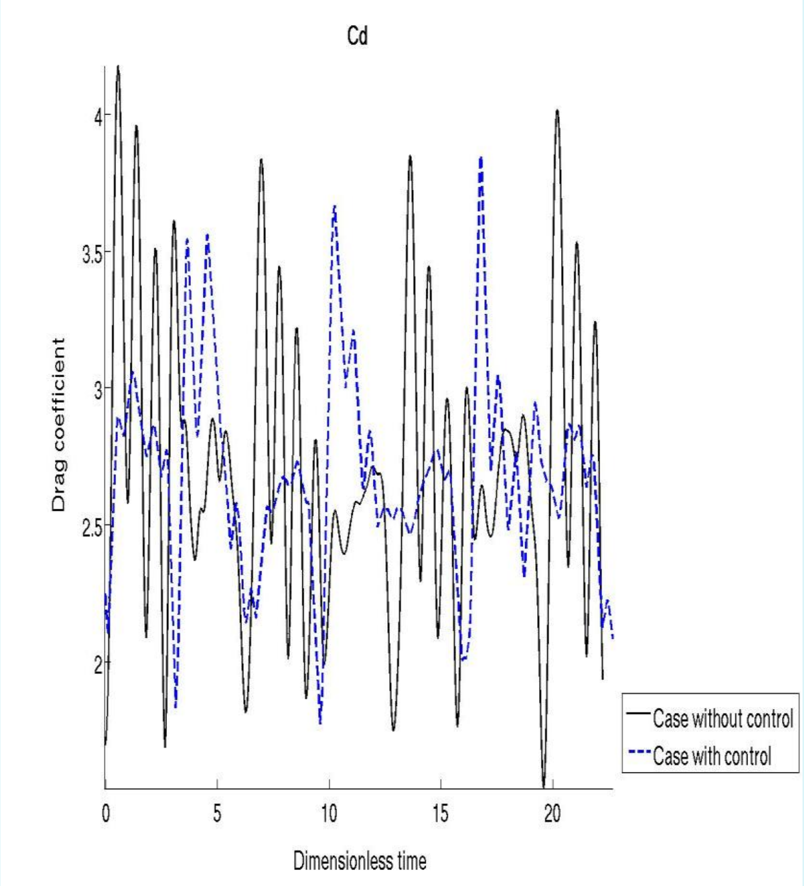
# Comparative Analysis of Drag & Lift – 45 degrees

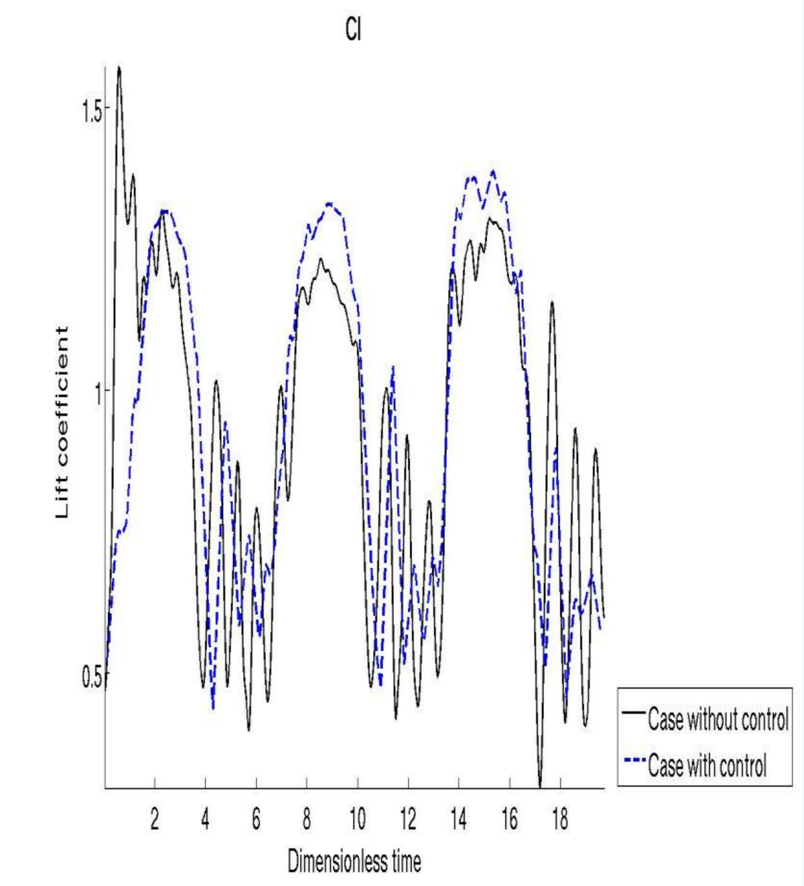



Exact synchronization

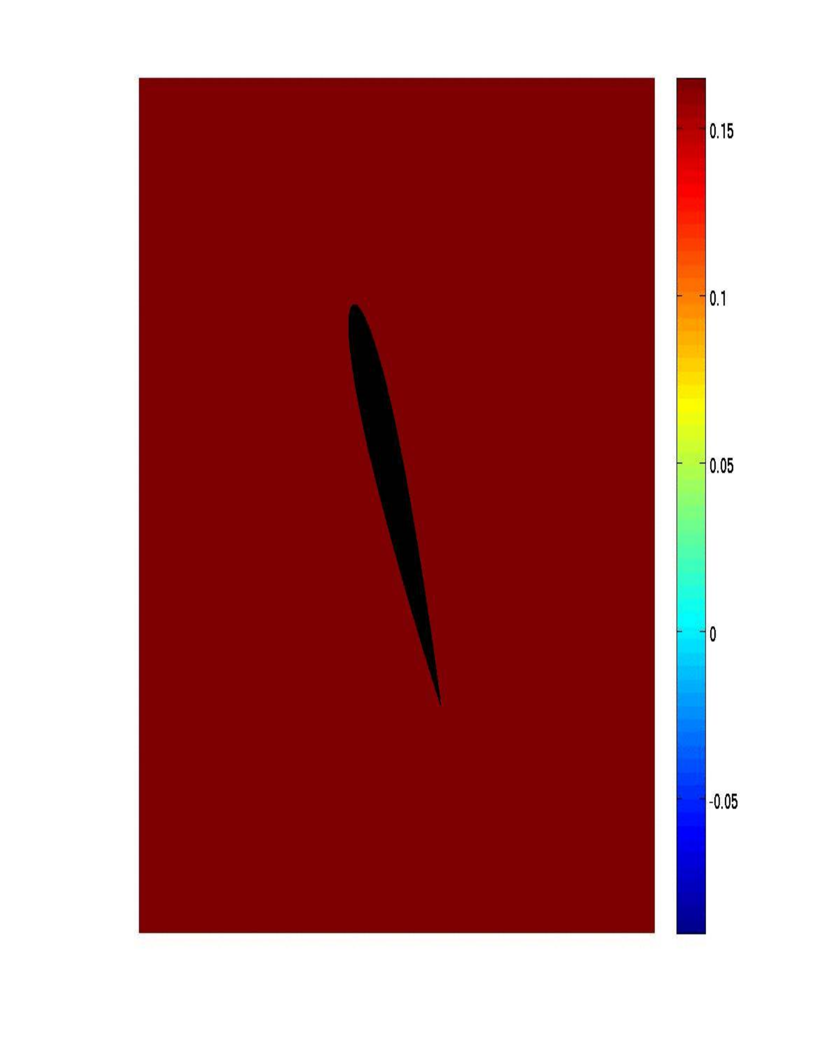
# Comparative Analysis of Drag & Lift – 70 degrees

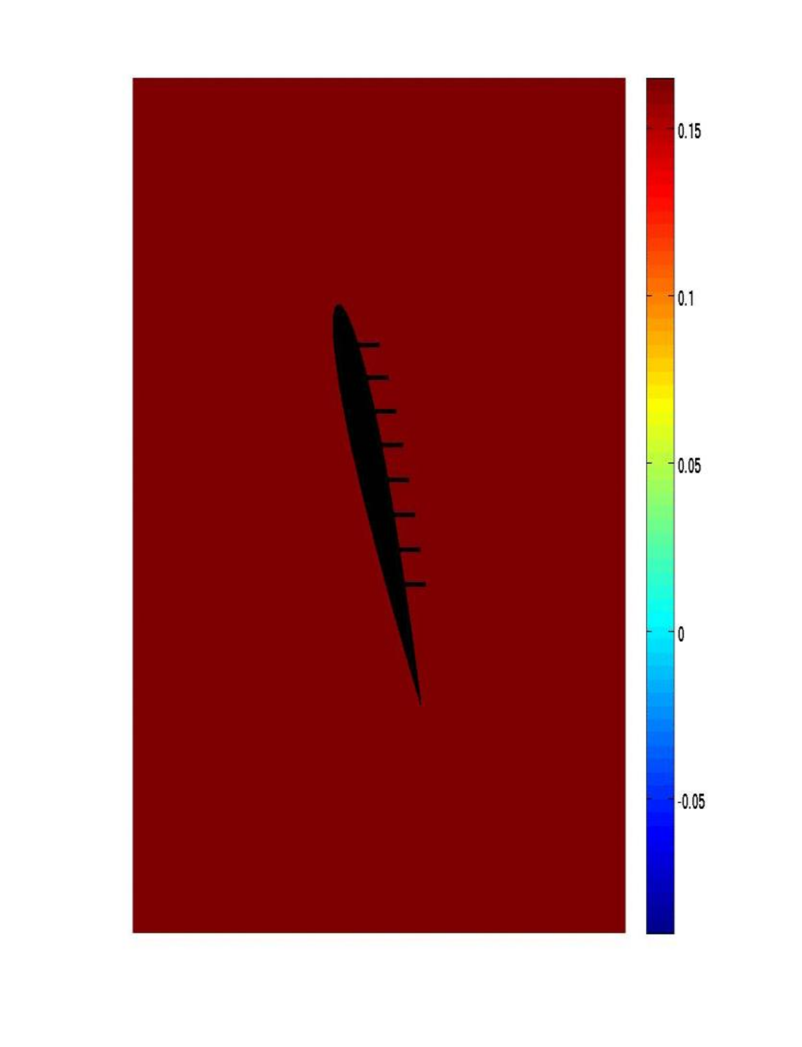



Approximate synchronization

# Comparative Analysis of Velocity Near the Airfoil– Without & With Control



# Comparative Analysis of Vortex Shedding – Without & With Control

Modification of the wake … uhm

# SUMMARY

Sets of control parameters are found which give enhanced aerodynamic performances with the following features:

- **For 22°:**
  Increase in mean lift – 32.24%, Decrease in lift oscillations – 16.74%, Decrease in drag oscillations – 37.44%, Mean drag increases – by 6.6%.

- **For 45°:**
  Decrease in mean lift – 9.23%, Decrease in drag fluctuations – 8.79%, Mean drag decreases – by 1.47%.

- **For 70°:**
  Increase in mean lift – 16.96%, Decrease in lift fluctuations – 25.75%, Decrease in drag fluctuations – 21.28%, Decrease in mean drag – approx. 1.48%.

Before you ask me …

# Before you ask me …

- How to convert model parameters into a choice for an effective material for the actuators? The “optimal” material may not be viable or may not even exist.
- How do you optimize?
- Must increase Re to render it more pertinent!
- What works at one Re/angle of attack may hamper performances for different sets of parameters …
- Etc.

# Will we ever get here?


*The Times of India*, April 16 2009