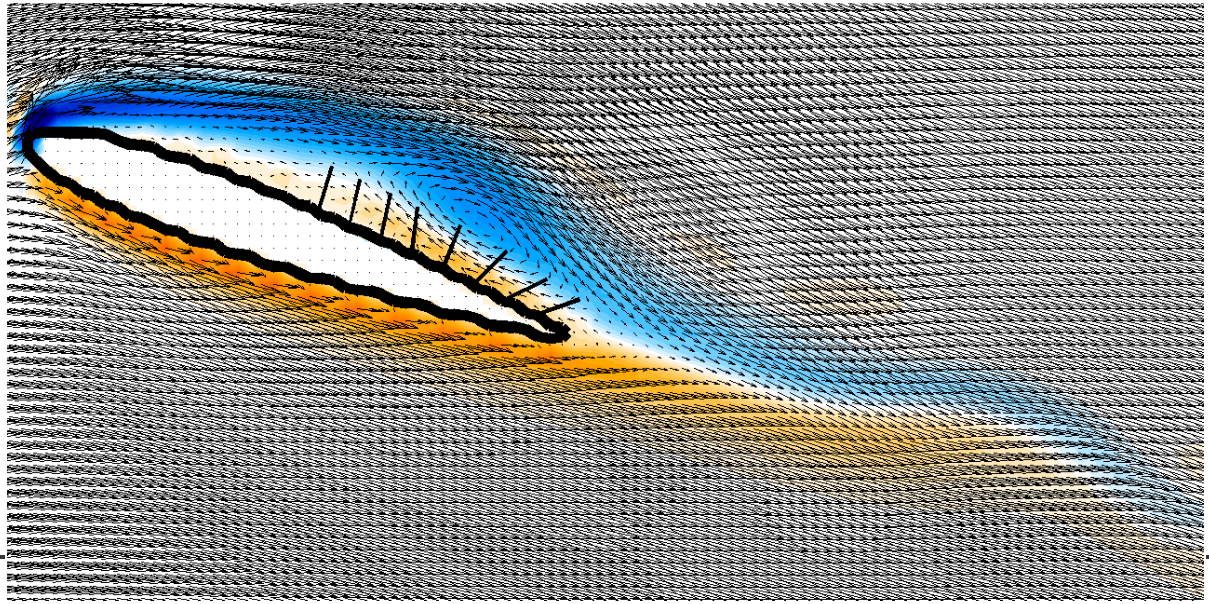

HAIRFOILS: PASSIVE ACTUATORS FOR FLOW CONTROL

A. Bottaro, J. Favier (DICAT, Genova)
&
A. Dauptain (CERFACS, Toulouse)

Fluid & Elasticity, Carry-le-Rouet, 23-26 june 2009

How can we reduce pressure drag behind a solid bluff body by a passive technique?

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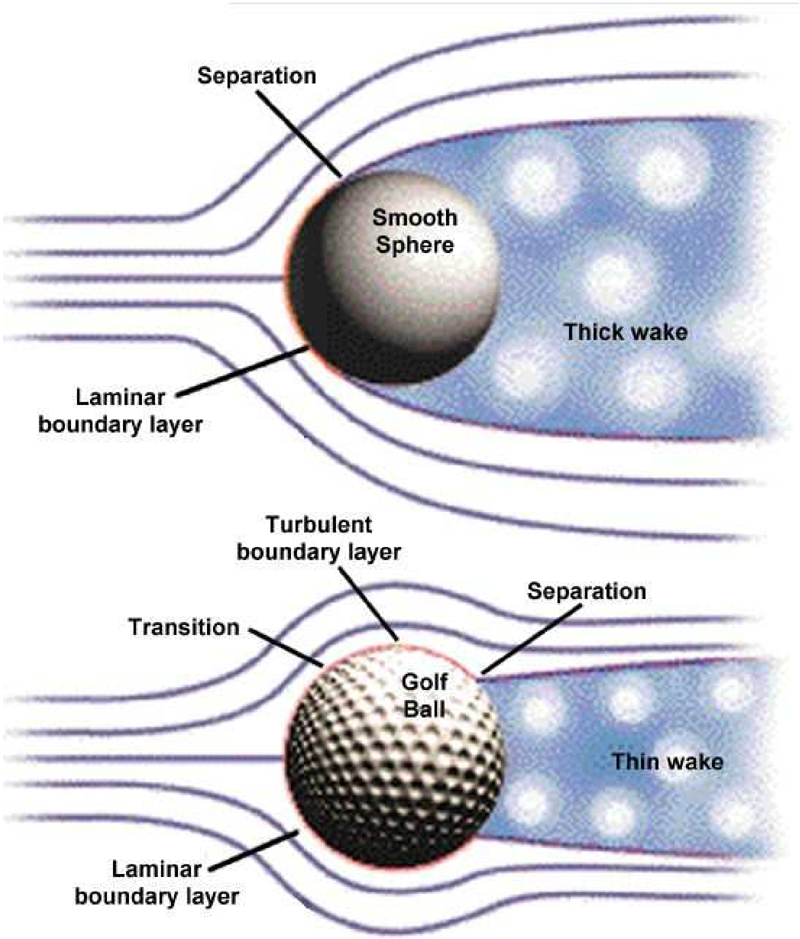

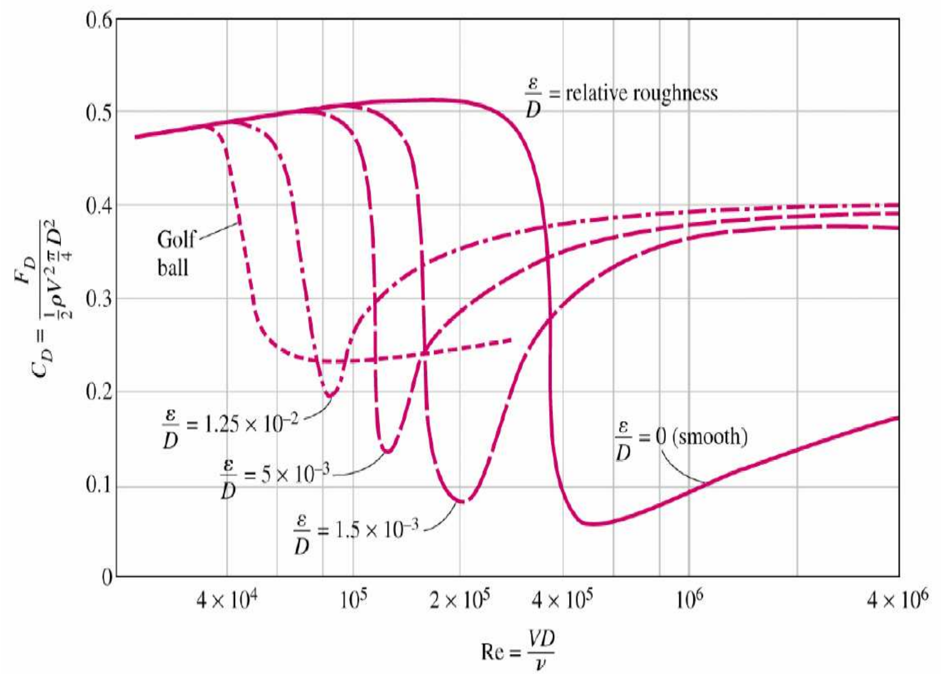

Known techniques of passive/active flow control:

- Injection of micro-bubbles and/or polymers
- Riblets
- Compliant walls
- Viscosity modifier
- Vortex generators
- …

Known techniques of passive and/or active flow control:

- Injection of micro-bubbles and/or polymers
- Riblets
- Compliant walls
- Viscosity modifier
- Vortex generators
- ...

Why not use a

passive hairy coating?

sea otter

How can we increase lift over a streamlined body at incidence by a passive technique?

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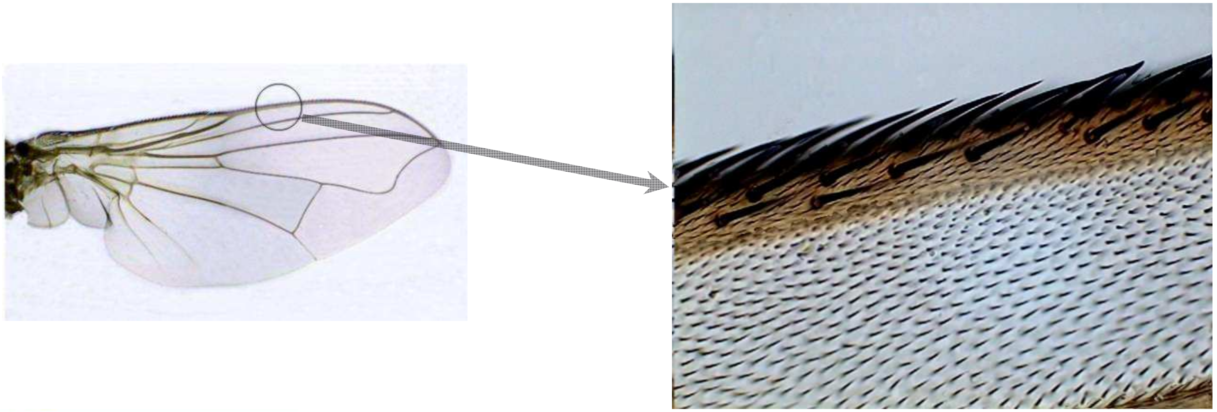
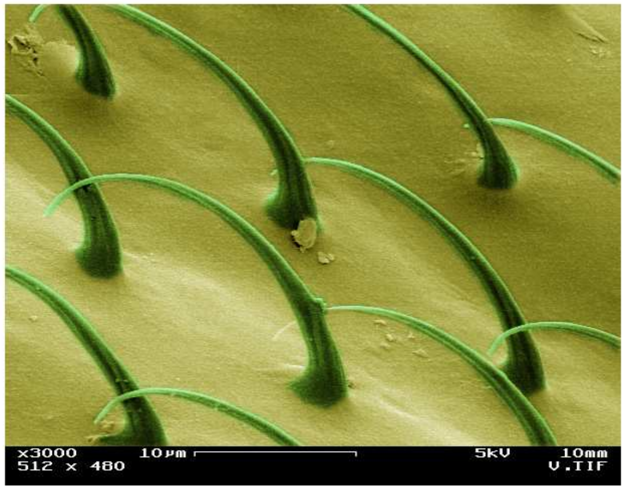


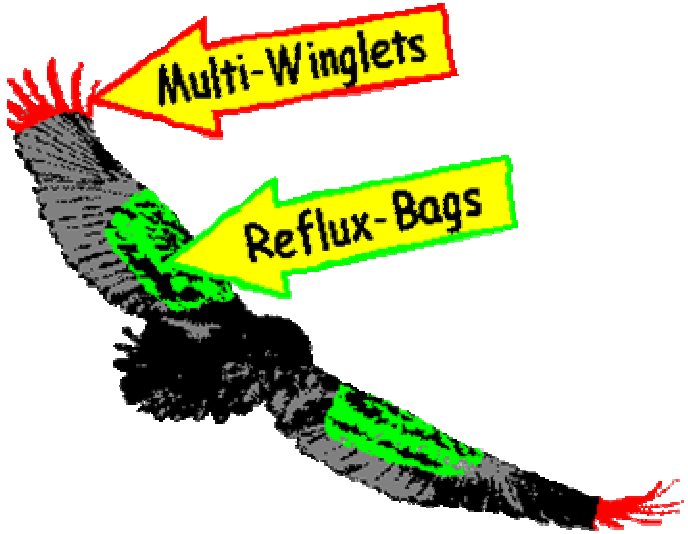


How can we increase lift over a streamlined body at incidence by a passive technique?

How can we increase lift over a streamlined body at incidence by a passive technique?

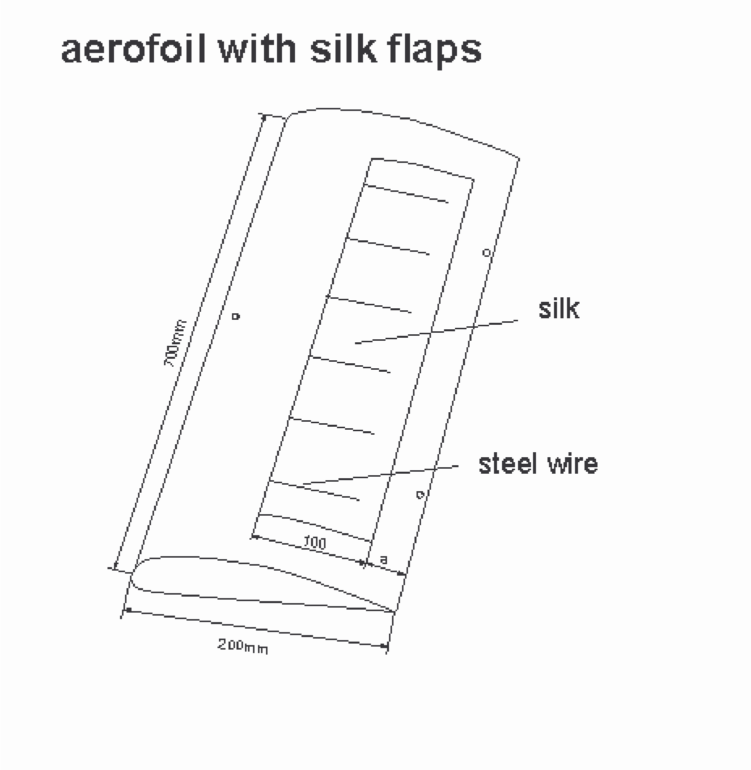
Coverts have also a aerodynamic role ...

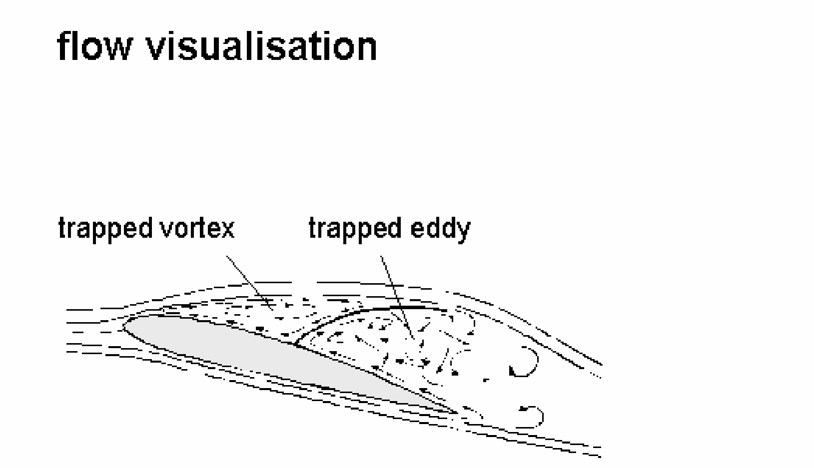
How can we increase lift over a streamlined body at incidence by a passive technique?



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

How can we increase lift over a streamlined body at incidence by a passive technique?





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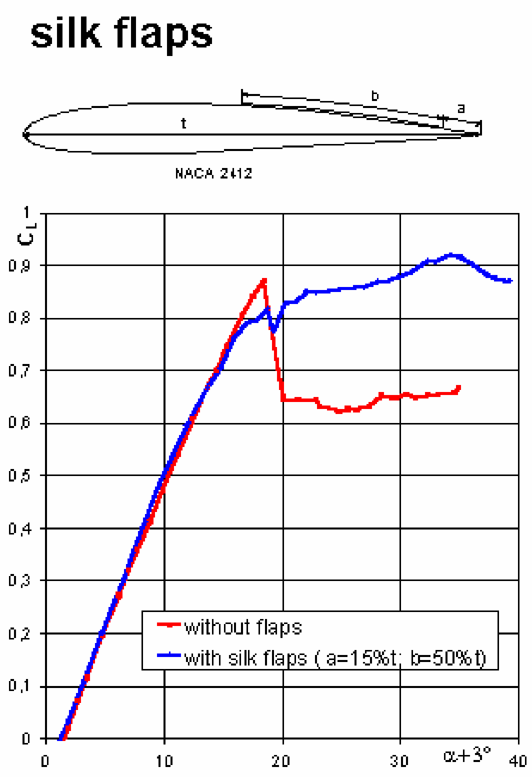
How can we increase lift over a streamlined body at incidence by a passive technique?

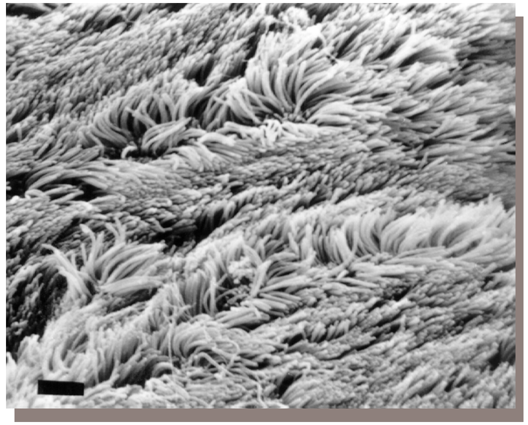


Flexible, porous flaps delay stall …

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

GOAL: instead of a single flexible flap, let’s model of a continuous *hairy/feathery* coating to affect lift and drag

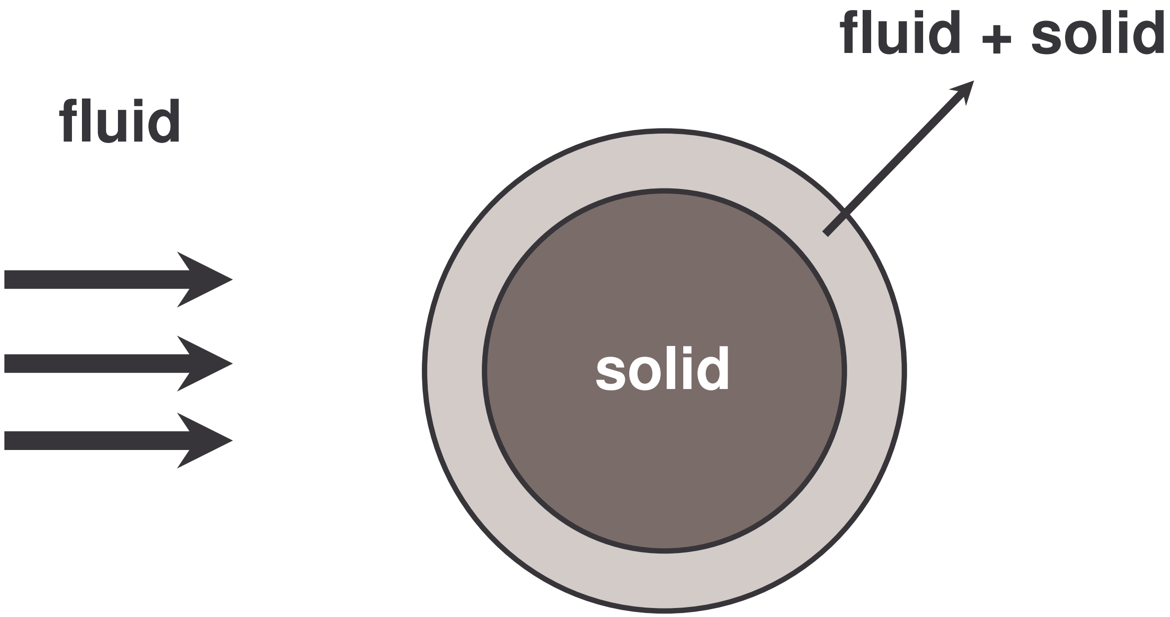
Numerical challenges



- **Model** mechanical properties **of biological surfaces**
- Structures with **large displacements** and **large rotations**
- Interaction between **multiple structures**

Coupling between a layer of oscillating densely packed structures and a unsteady separated boundary layer

The initial configuration



Circular cylinder, Re=200

Model of the layer?

Porous, anisotropic and compliant

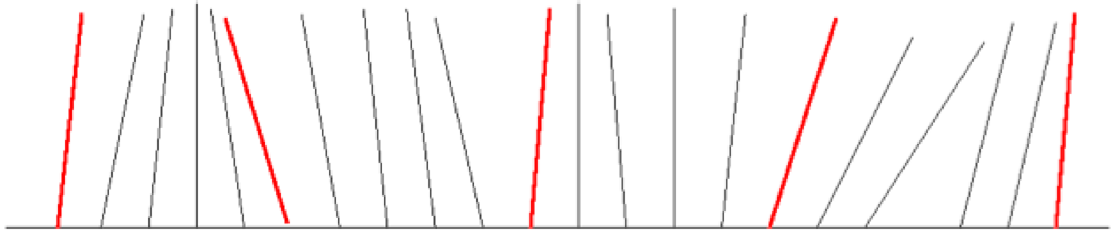
Modeling in 3 points

Modeling all feathers: too heavy …

→ **Must reduce the numbers of degrees of freedom**

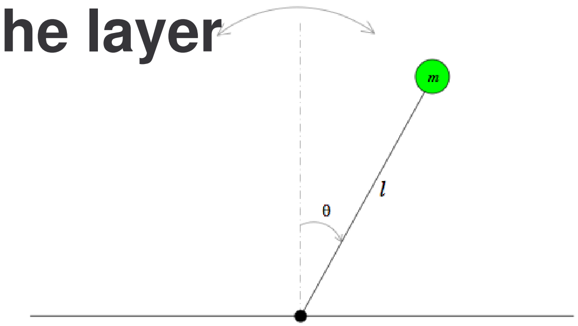
1. **Homogenized approach**: description of the layer in terms of **density** and **direction** of feathers.
2. Motion of the layer reduces to the oscillation of a small number of **reference elements**
3. The fluid “sees” the structures in terms of **volume forces** (and the same for the structures)

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

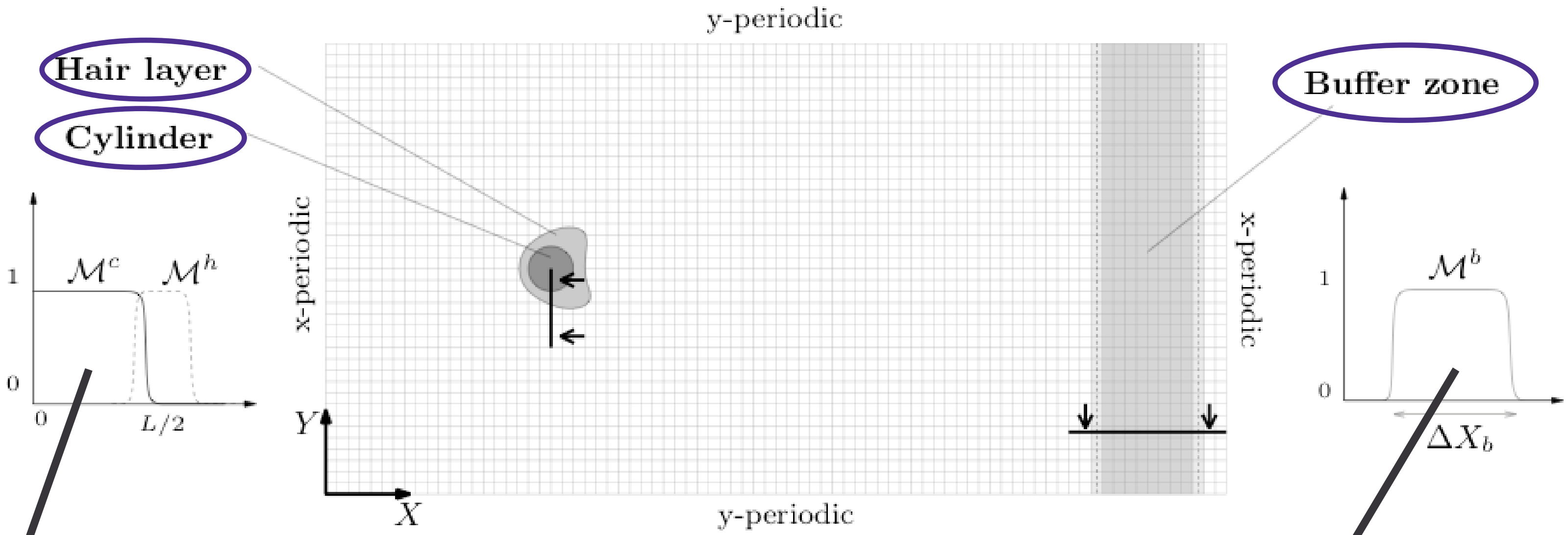
Convective part: Adams-Bashfort
Viscous part: Crank-Nicolson
Poisson and implicit parts solved using conjugate gradient

→ order 2 in space and time

Fluid part ...

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

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



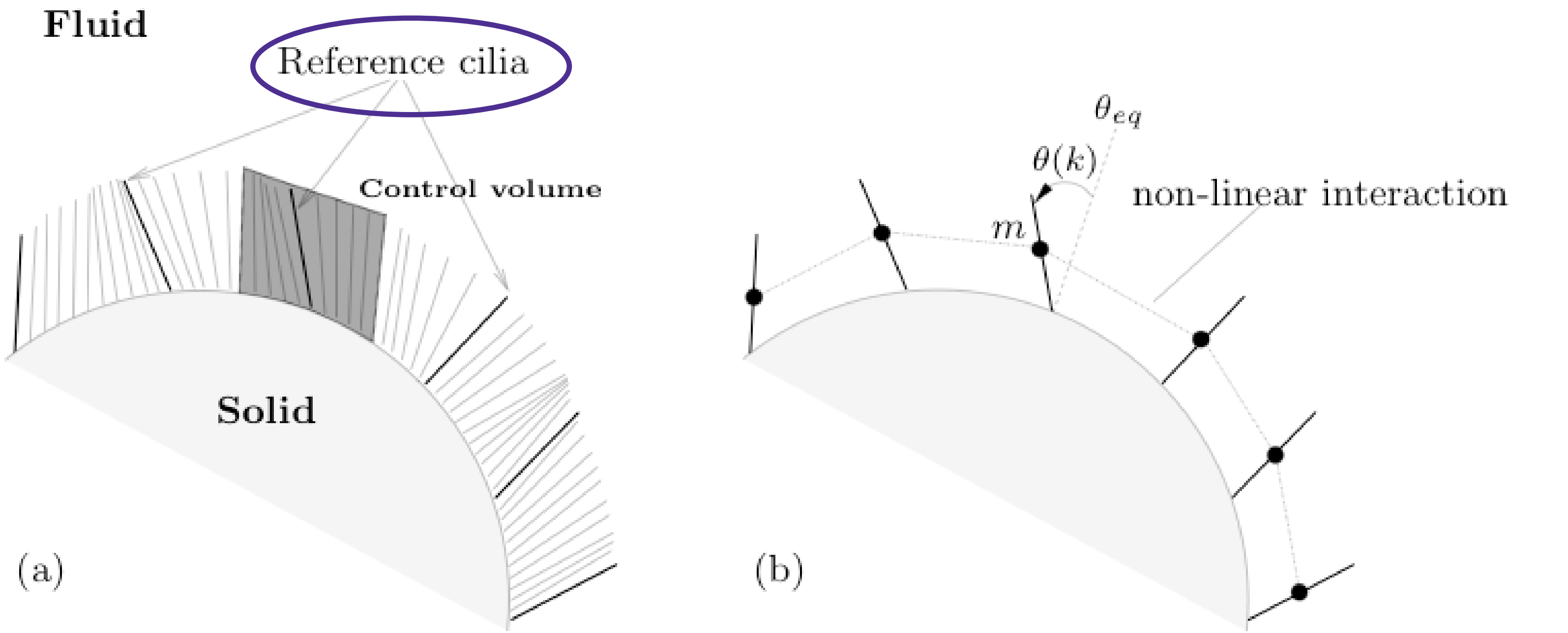
$$\mathbf{F}^c = \mathcal{M}^c \left(\alpha^c \int_{t_0}^{t} (\mathbf{0} - \mathbf{U})\, dt + \beta^c (\mathbf{0} - \mathbf{U}) \right)$$

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

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

Structure part ...

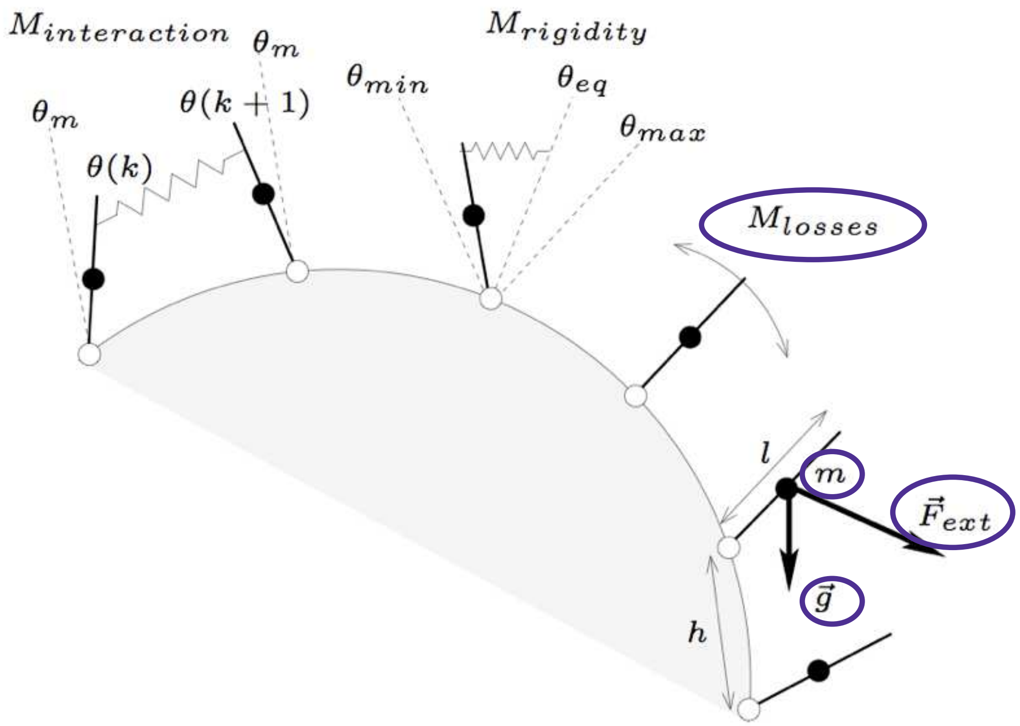
"skeleton" of
the layer



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

Structure part ...

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



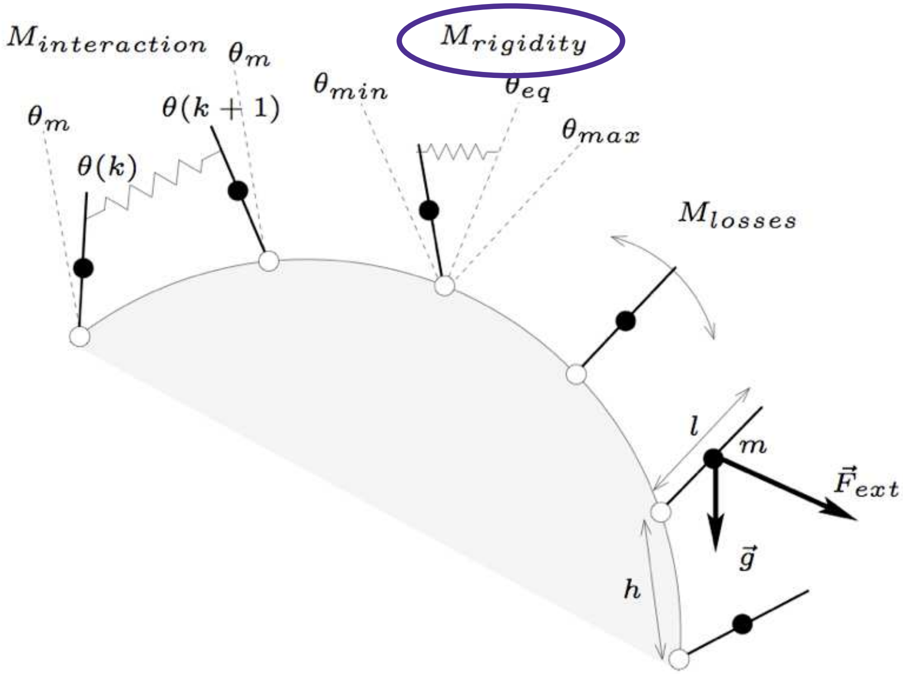
$$M_{losses}(k) = -K_l\,\dot{\theta}(k)$$

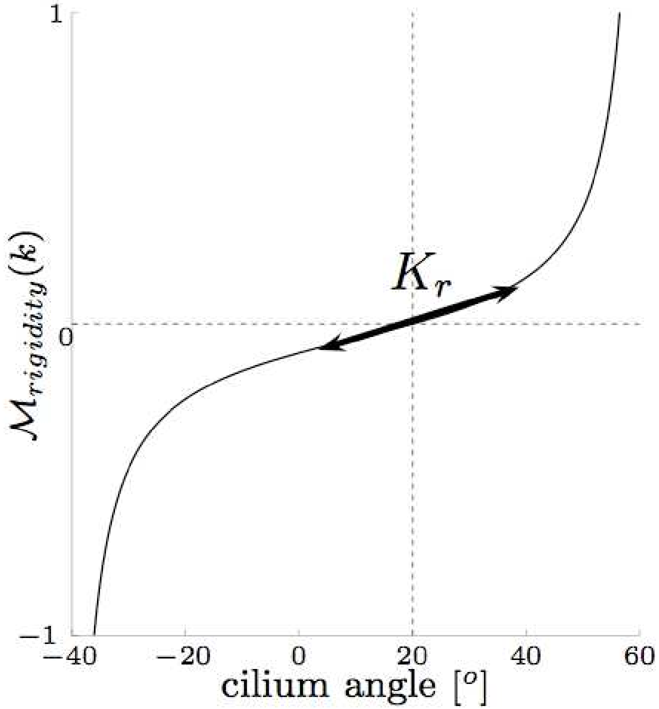
$$M_{inertia}(k) = -m\frac{l^2}{4}\ddot{\theta}(k)$$

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

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

Structure part ...

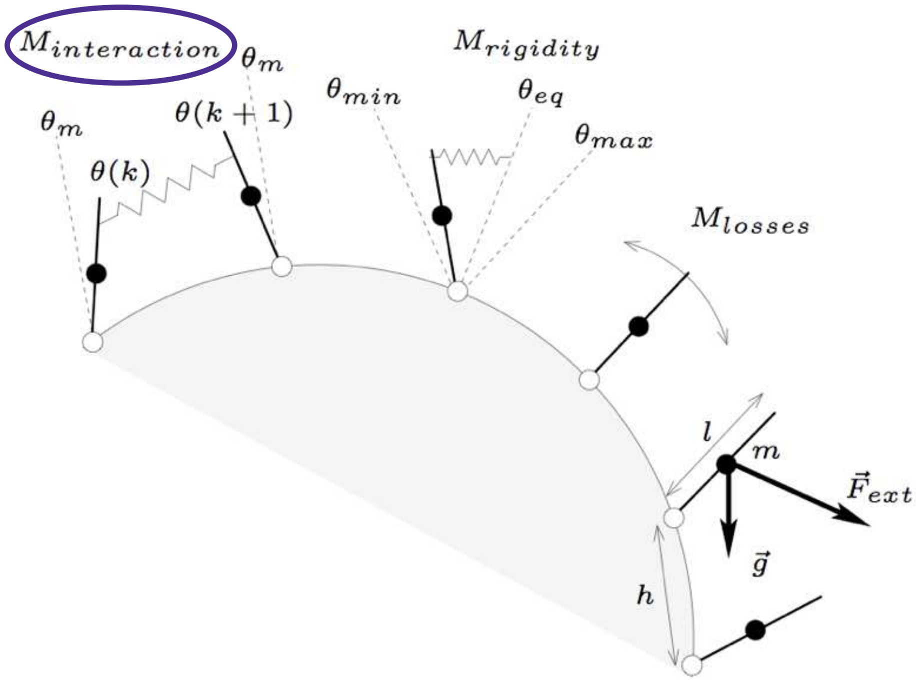


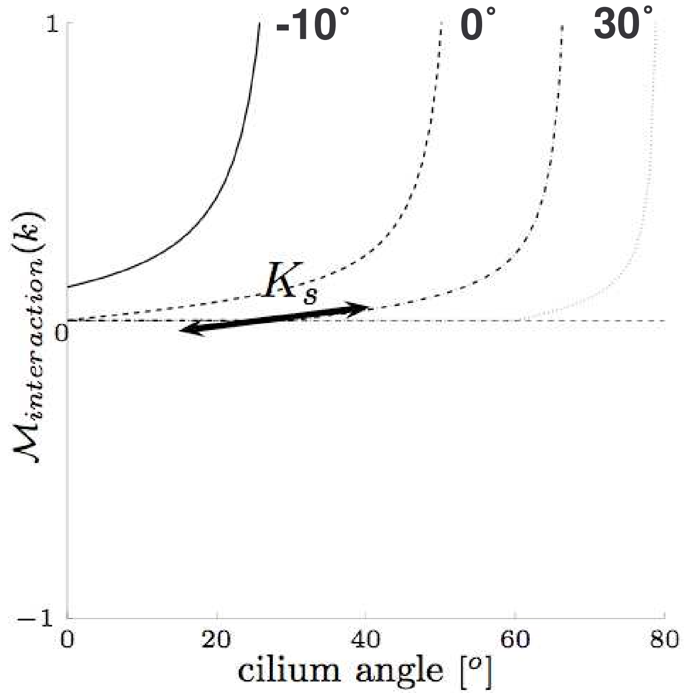


$$M_{rigidity}(k) = -K_r \frac{P(\theta) - P(\theta_{eq})}{P'(\theta_{eq})}$$

avec $P = \tan(a\theta + b)$ $\quad a = \pi/(\theta_{max} - \theta_{min})$, $\quad b = -a(\theta_{max} + \theta_{min})/2$

Structure part ...





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

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

Structure part ...

Explicit resolution: Runge-Kutta 4

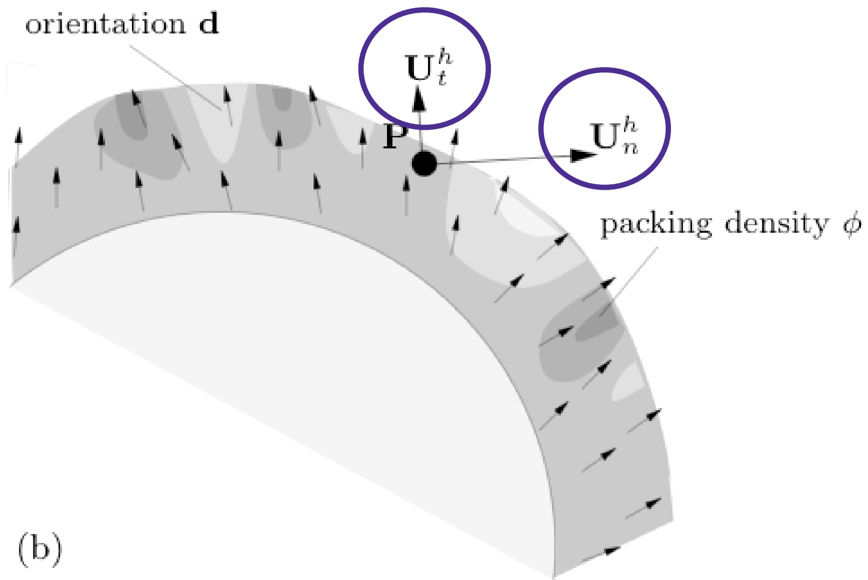
$$m(l/2)^2\ddot{\theta}(k) = M_{spring}(k) + M_{rigidity}(k) + M_{dissip}(k) + M_{inertia}(k) + M_{ext}(k) \ , \ k = 1, \ldots, N_c$$

Equilibrium is reached after a sufficient number of sub-iterations
For small masses: oscillations at long subtimes

Implicit resolution: Non-linear Conjugate gradient

$$M_{inertia}(k) + M_{spring}(k) + M_{rigidity}(k) + M_{dissip}(k) + M_{inertia}(k) + M_{ext}(k) \ , \ k = 1, \ldots, N_c$$

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

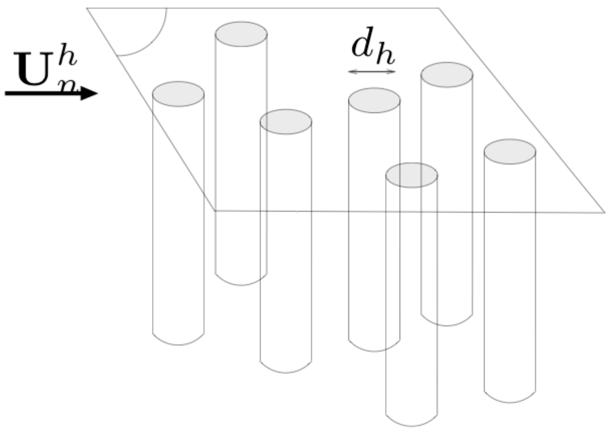


Decomposition of the local relative velocity into a tangential and a normal contribution

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) — $c_0(\phi)$

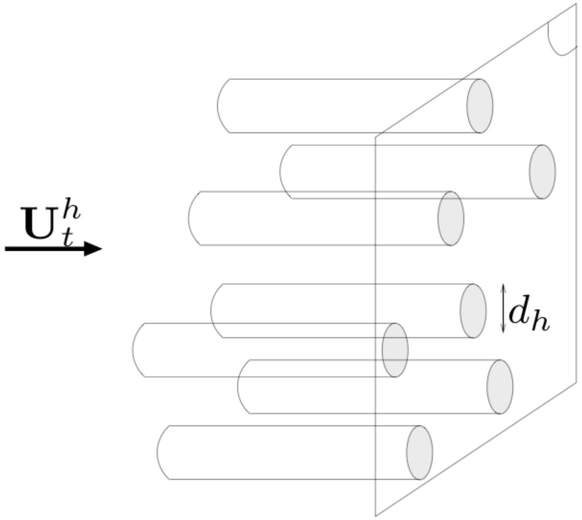
empirical Re<180 — $c_1(\phi)$

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:

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

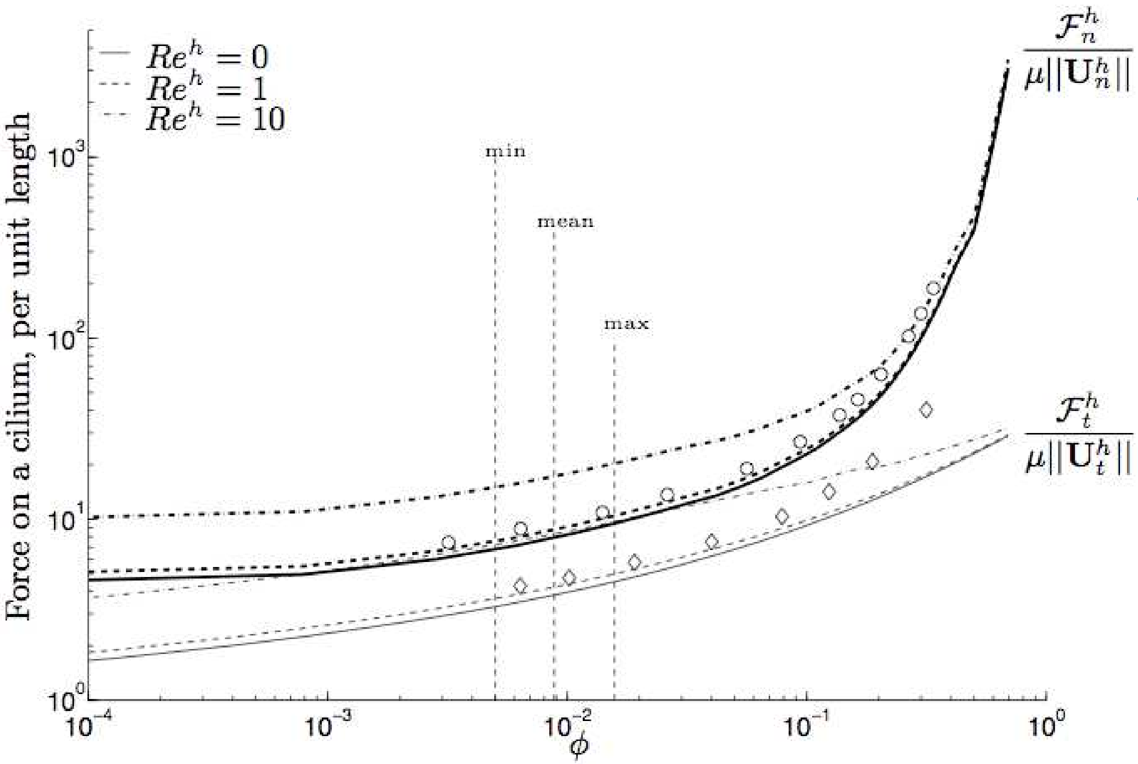
$\mathbf{U}_t^h(1-\phi)$: local velocity through the pores

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

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

Homogenized part (fluid+structure) ...

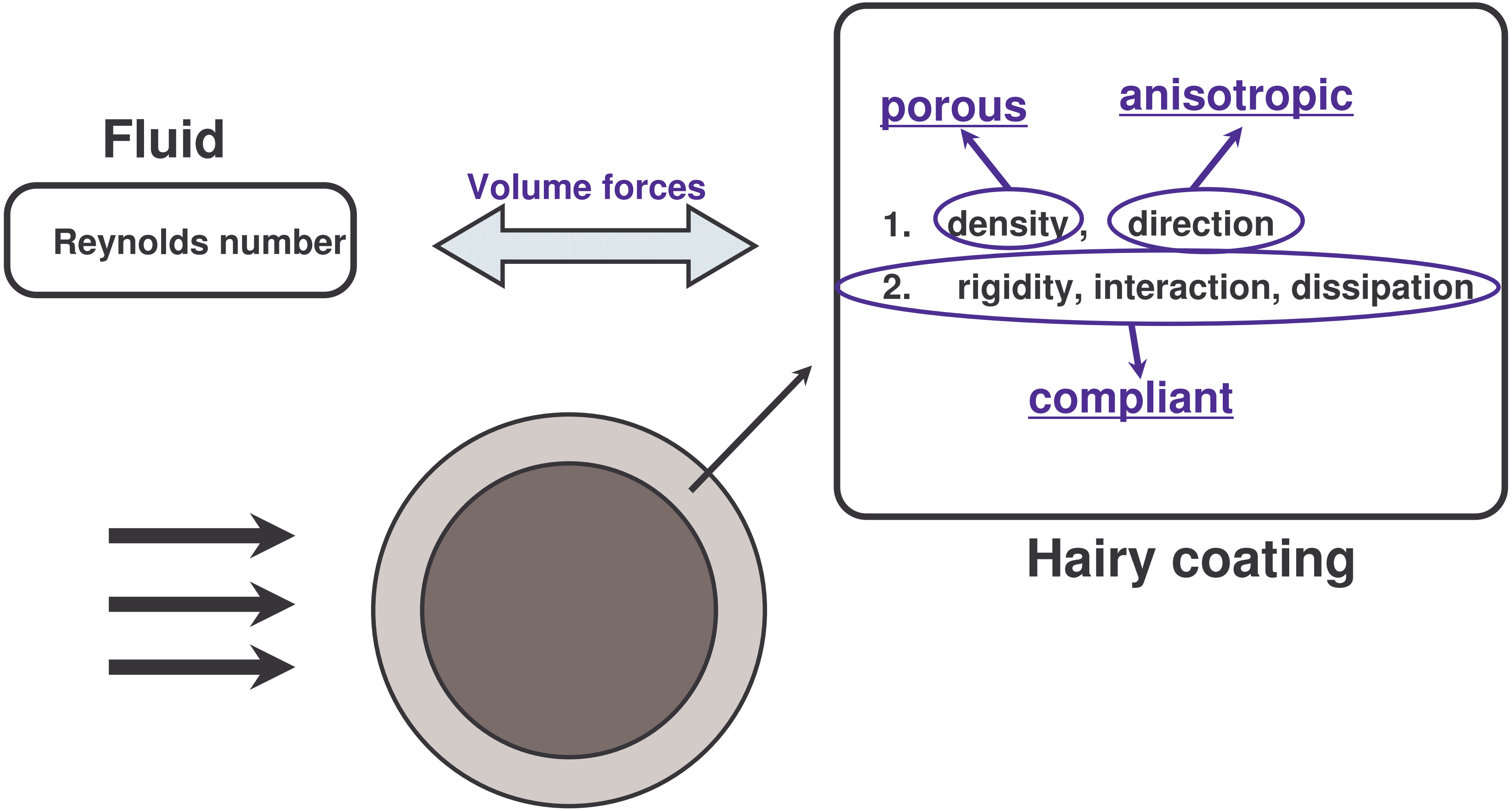
<u>Inner constants of the layer:</u>
Density (nb/cm2),
Diameter of cilia



Symbols :
theoretical model by
Howells, JFM 1997

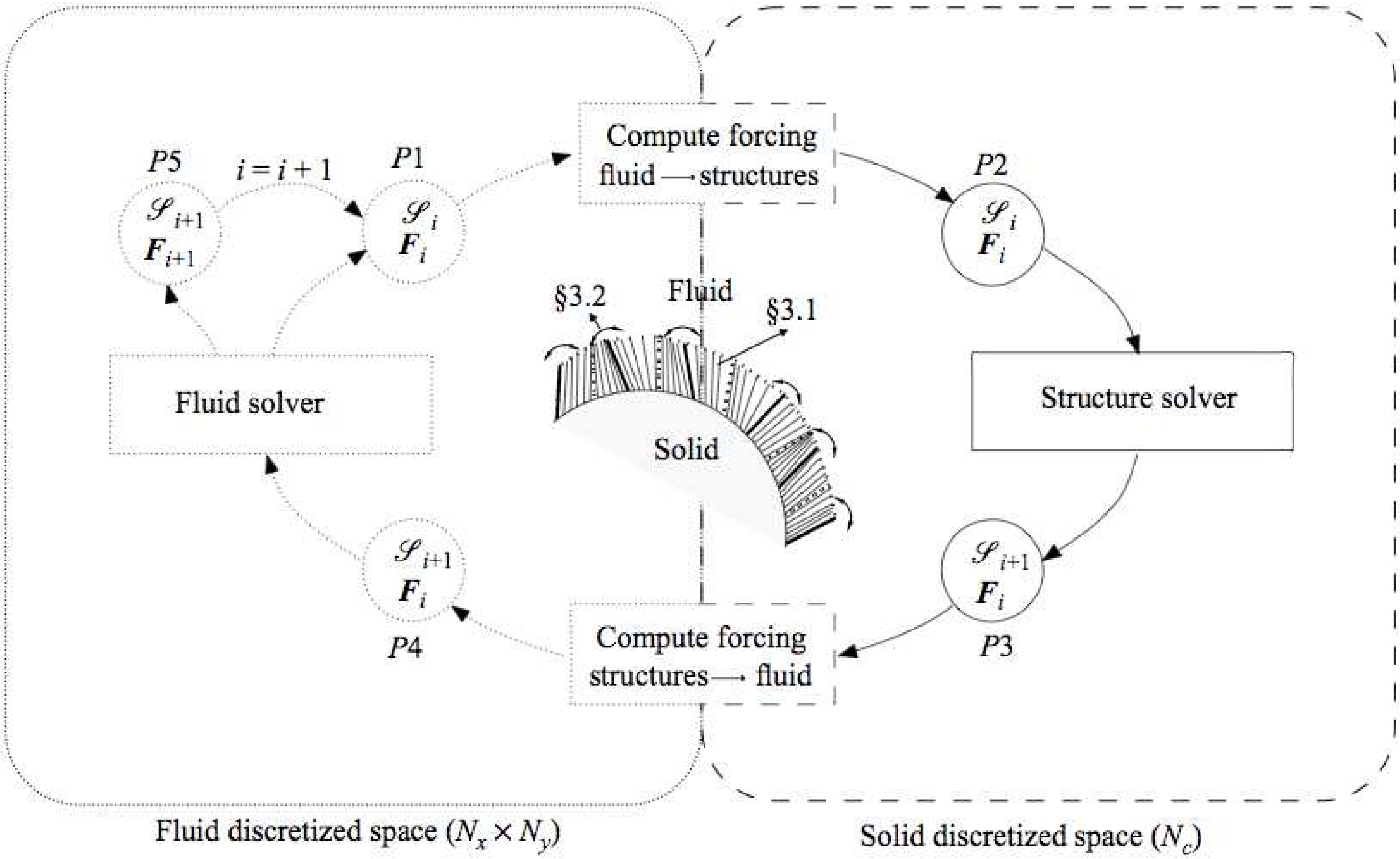
$$\longrightarrow \quad F_{ext}(k) = \int_{V_{control}(k)} \left\| \boldsymbol{F}^h \right\| \mathrm{d}V$$

Global overview



Algorithm

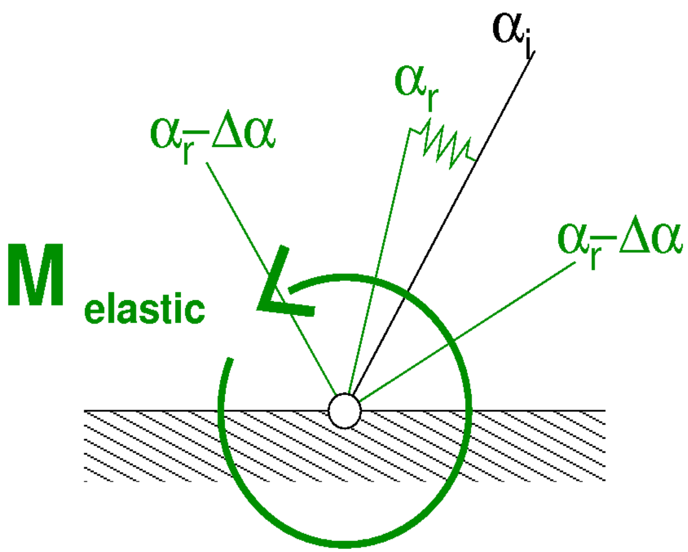
Partitioned staggered in time



All routines in f90

Parallelized (auto and openmp), portable and runs on clusters

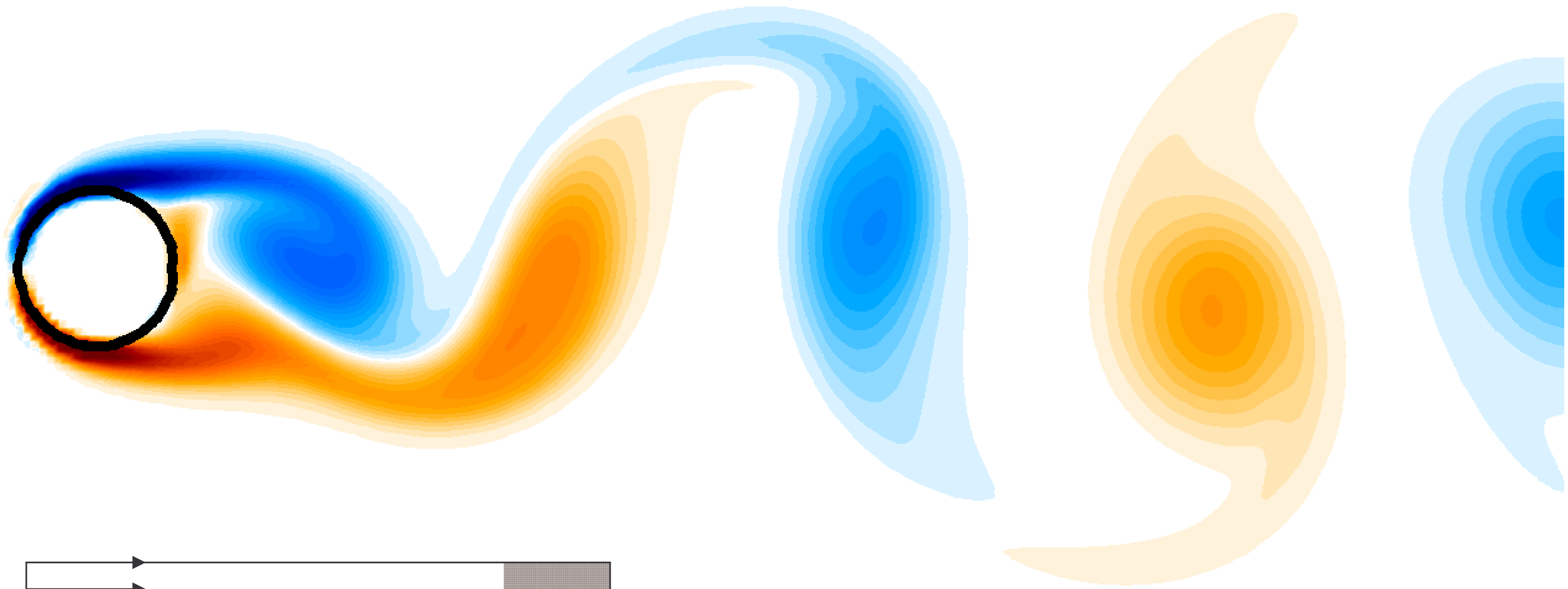
In the structural model, the rigidity/elastic term, which models the structural flexibility of the hairy layer, is the most significant. It defines a natural time scale of the layer, through which a coupling with the fluid is allowed

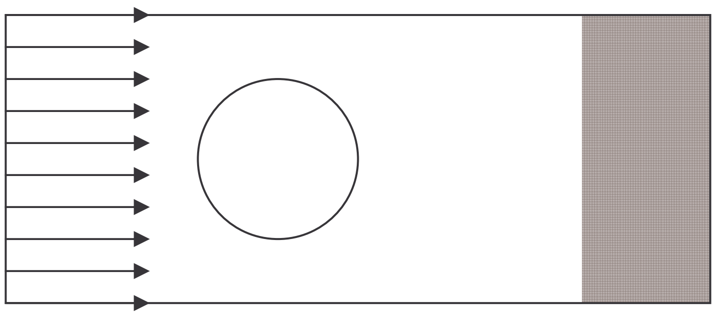


$$T_{structure} \approx \pi\, l\, \sqrt{(m/K_r)}$$

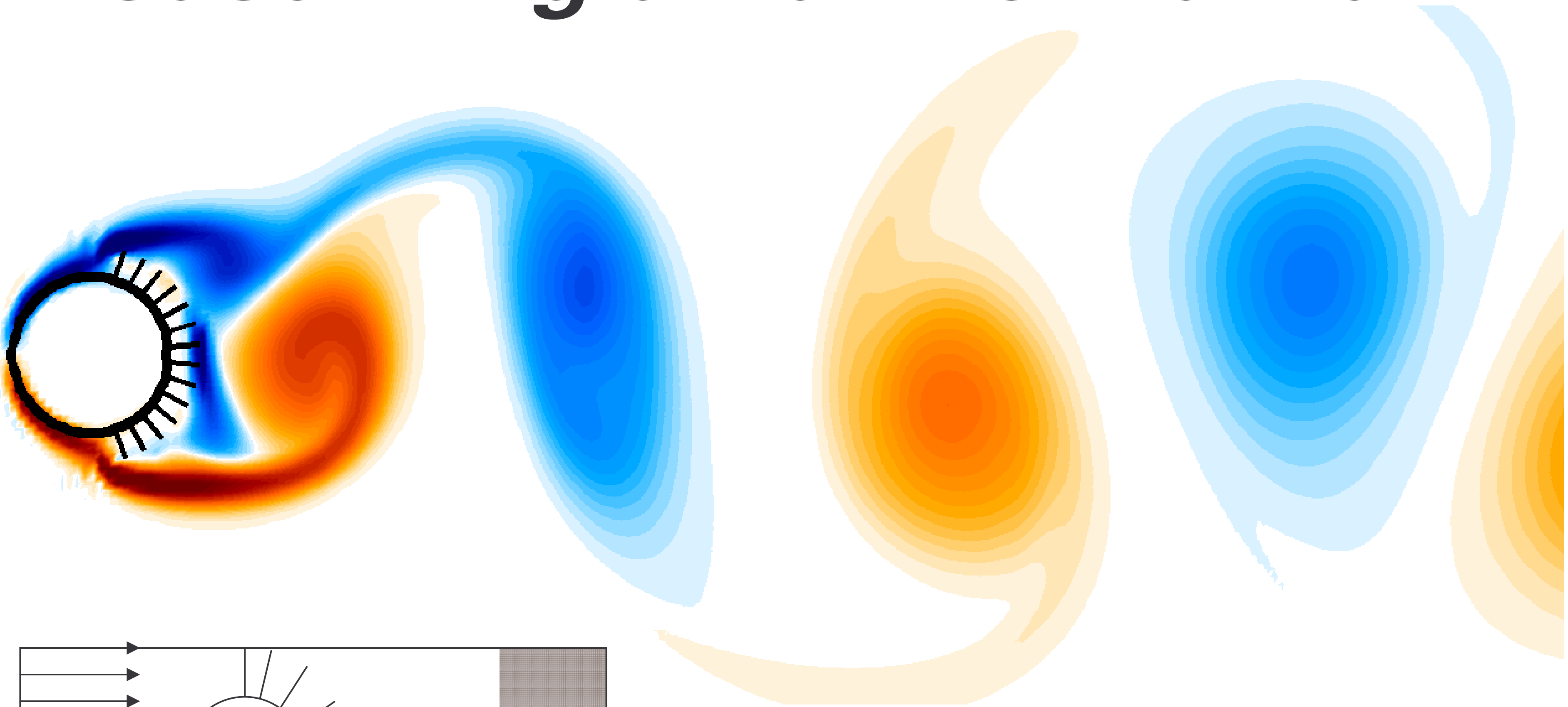
$$T_{fluid} \approx St^{-1}\; D/U_\infty$$

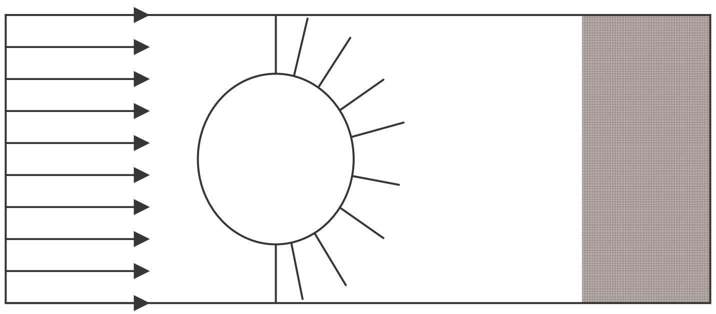
Case 1: bare cylinder



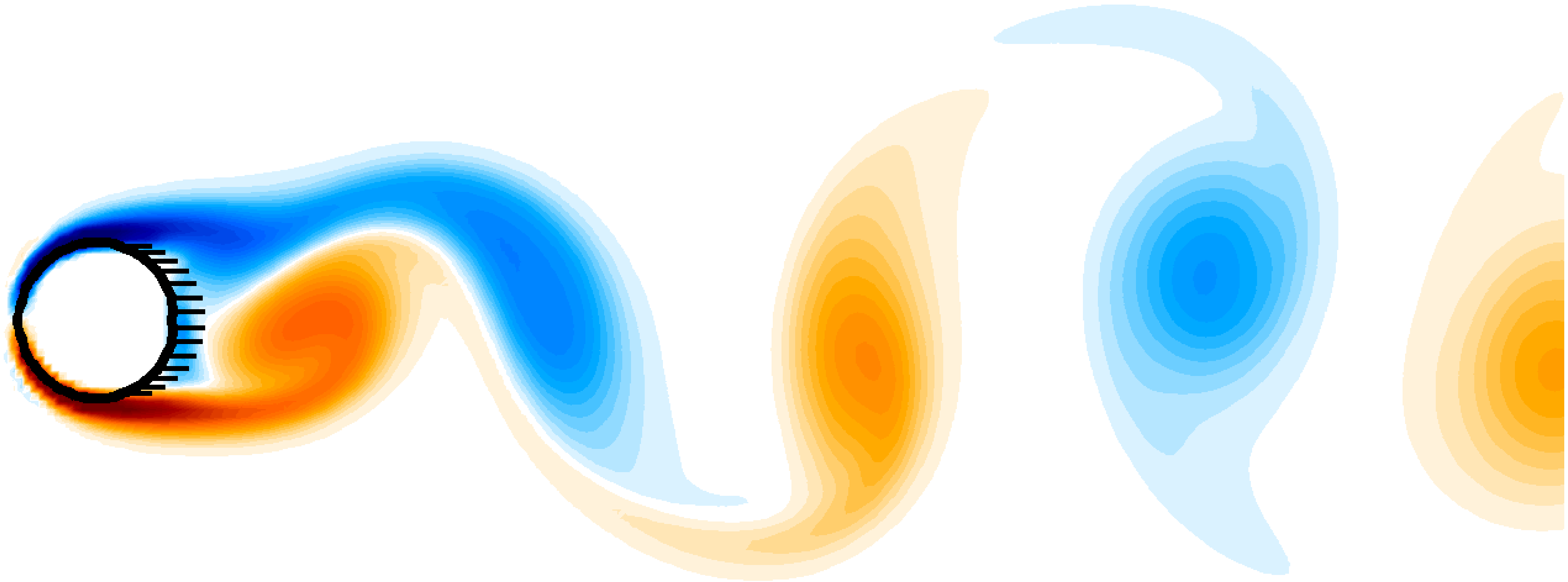


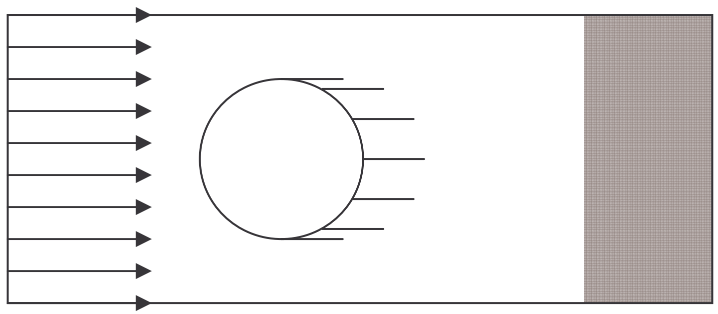
Case 2: rigid wall-normal hair



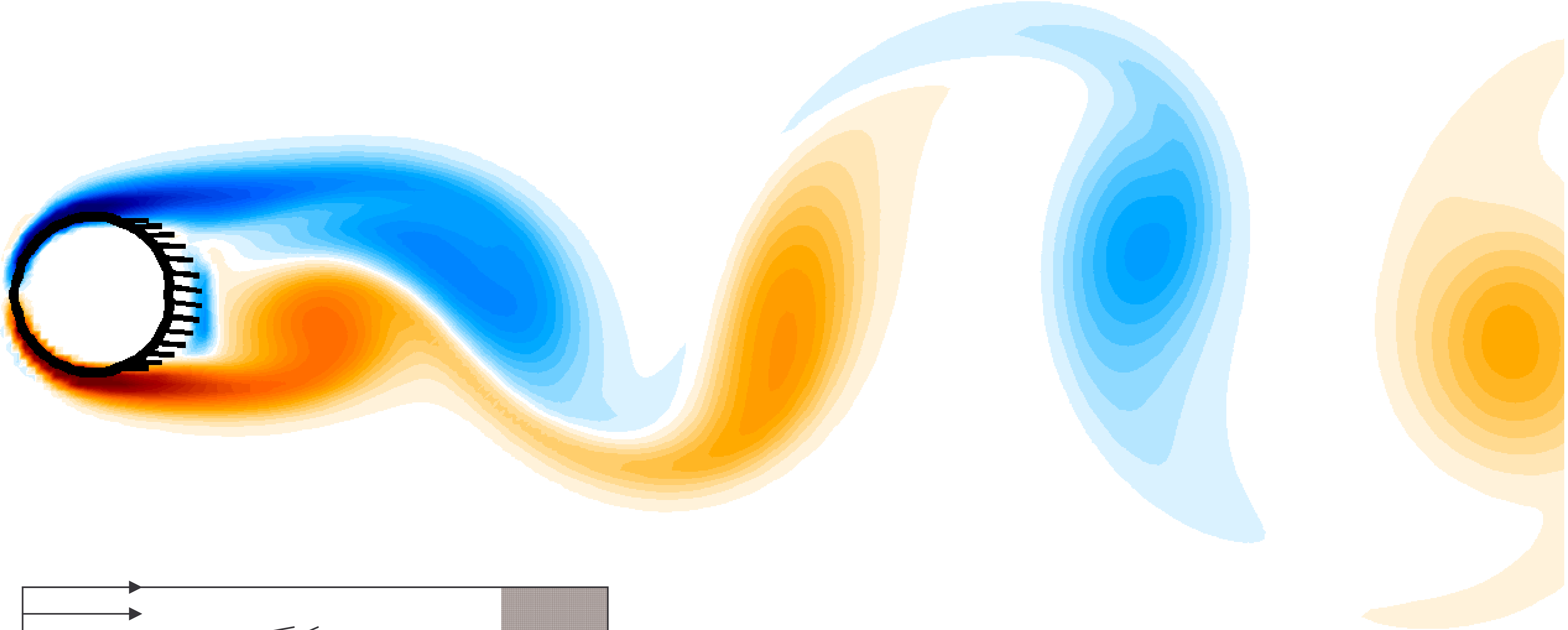


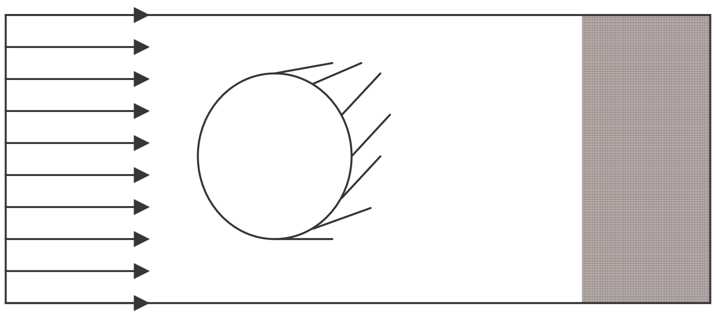
Case 3: rigid longitudinal hair





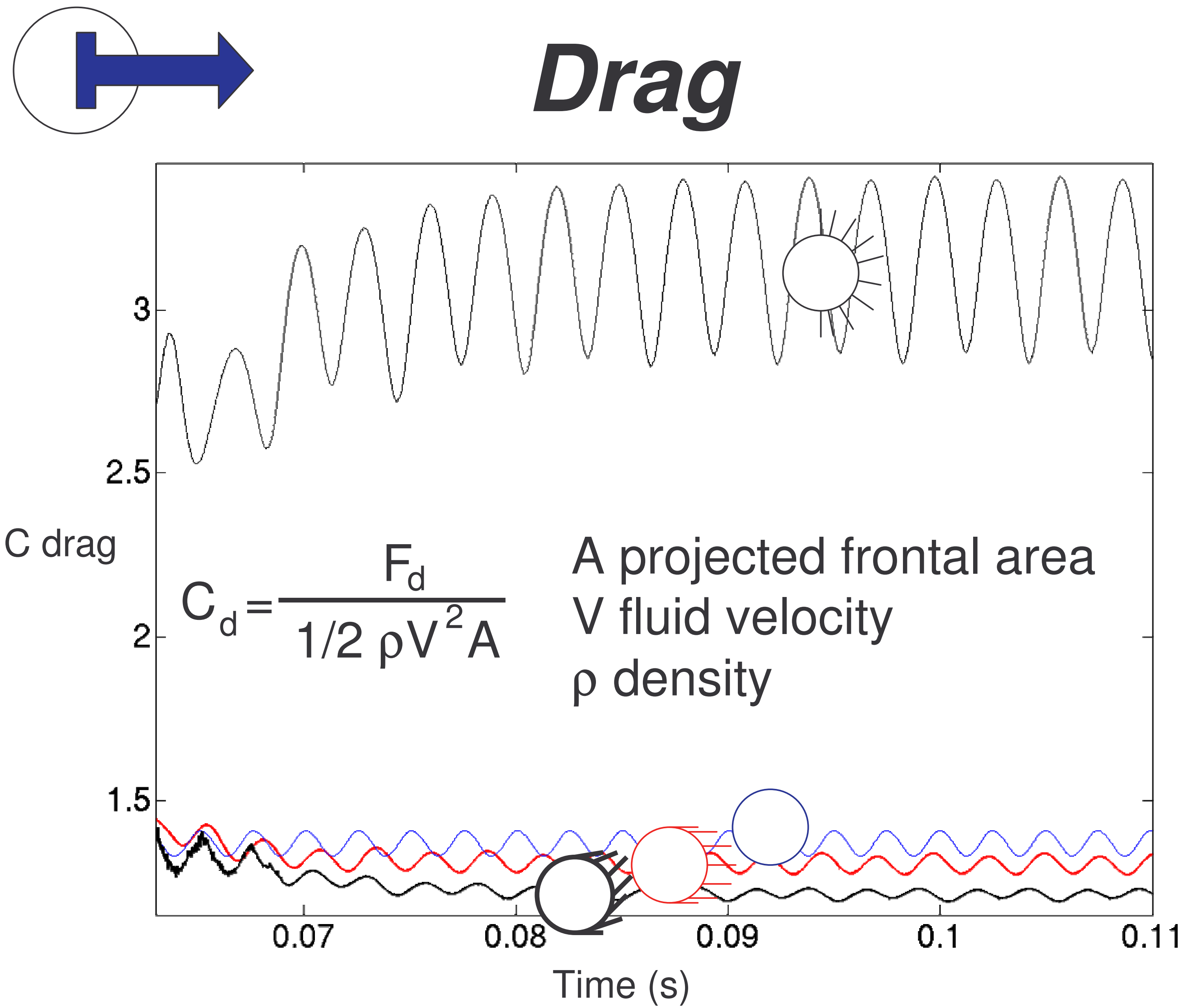
Case 4: moving hair





$T_{fluid} \approx 4\ T_{structure}$

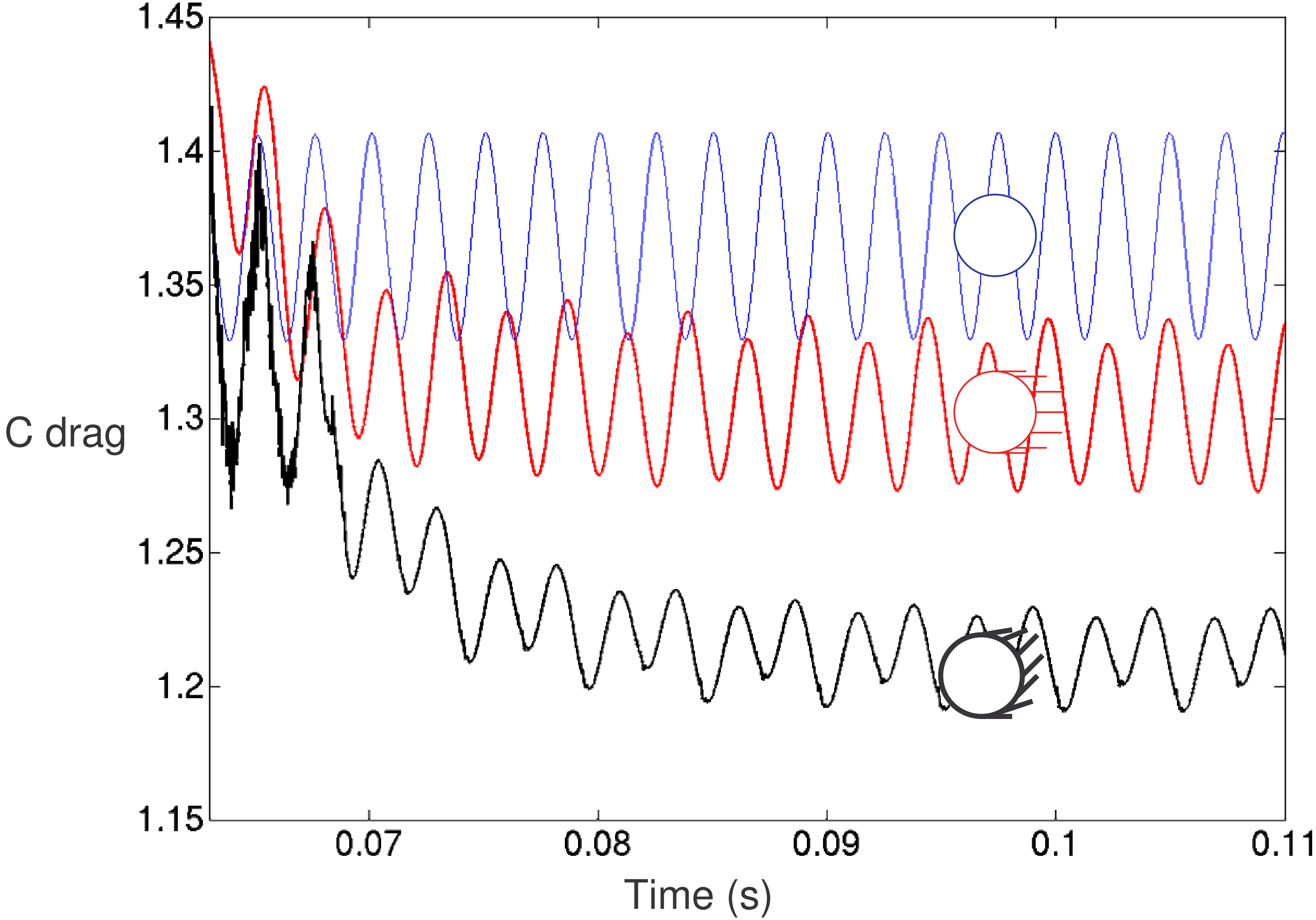
Drag



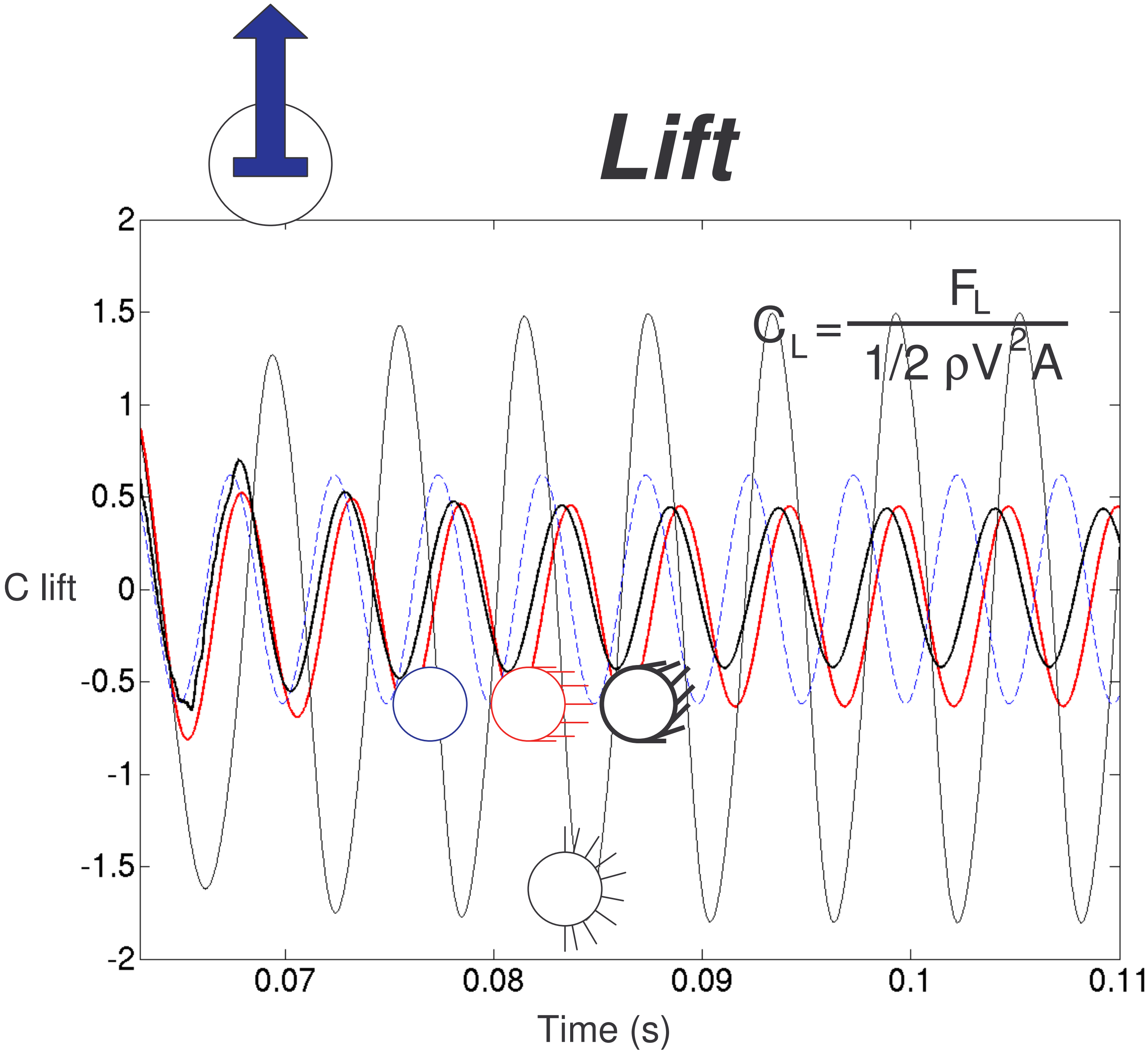
$$C_d = \frac{F_d}{1/2\,\rho V^2 A}$$

A projected frontal area
V fluid velocity
ρ density

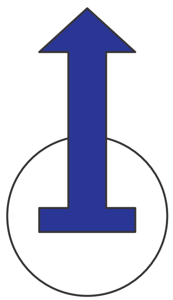
Drag (ctd.)



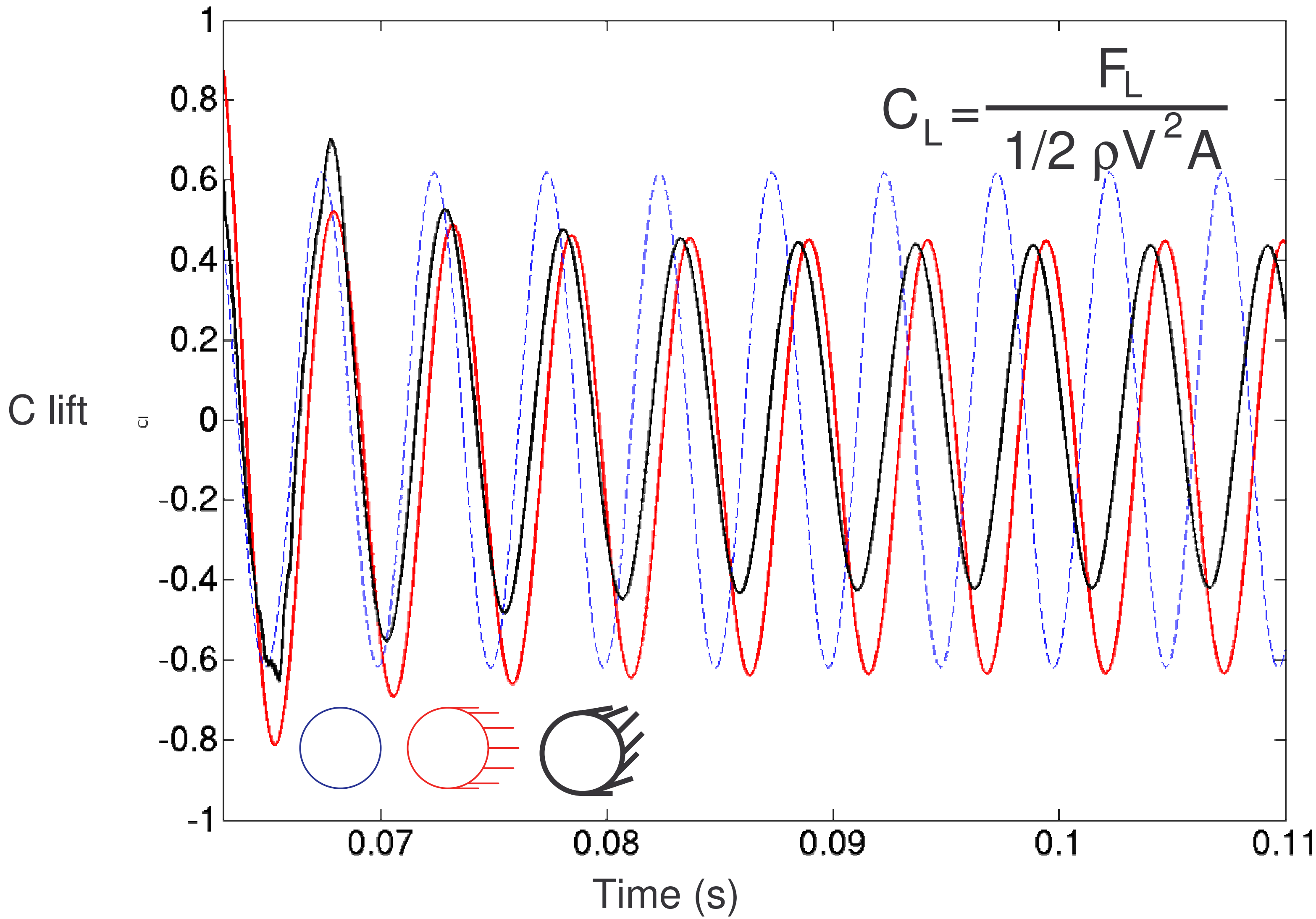
Lift



$C_L = \frac{F_L}{1/2\,\rho V^2 A}$
C lift
Time (s)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.07
0.08
0.09
0.1
0.11

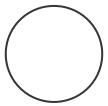
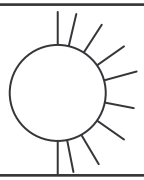
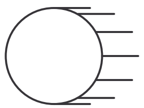
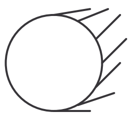


Lift (ctd.)



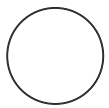
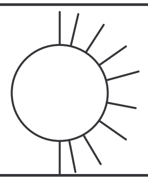
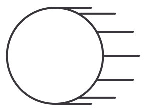
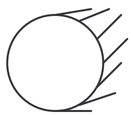
$$C_L = \frac{F_L}{1/2\, \rho V^2 A}$$

Aerodynamic performances

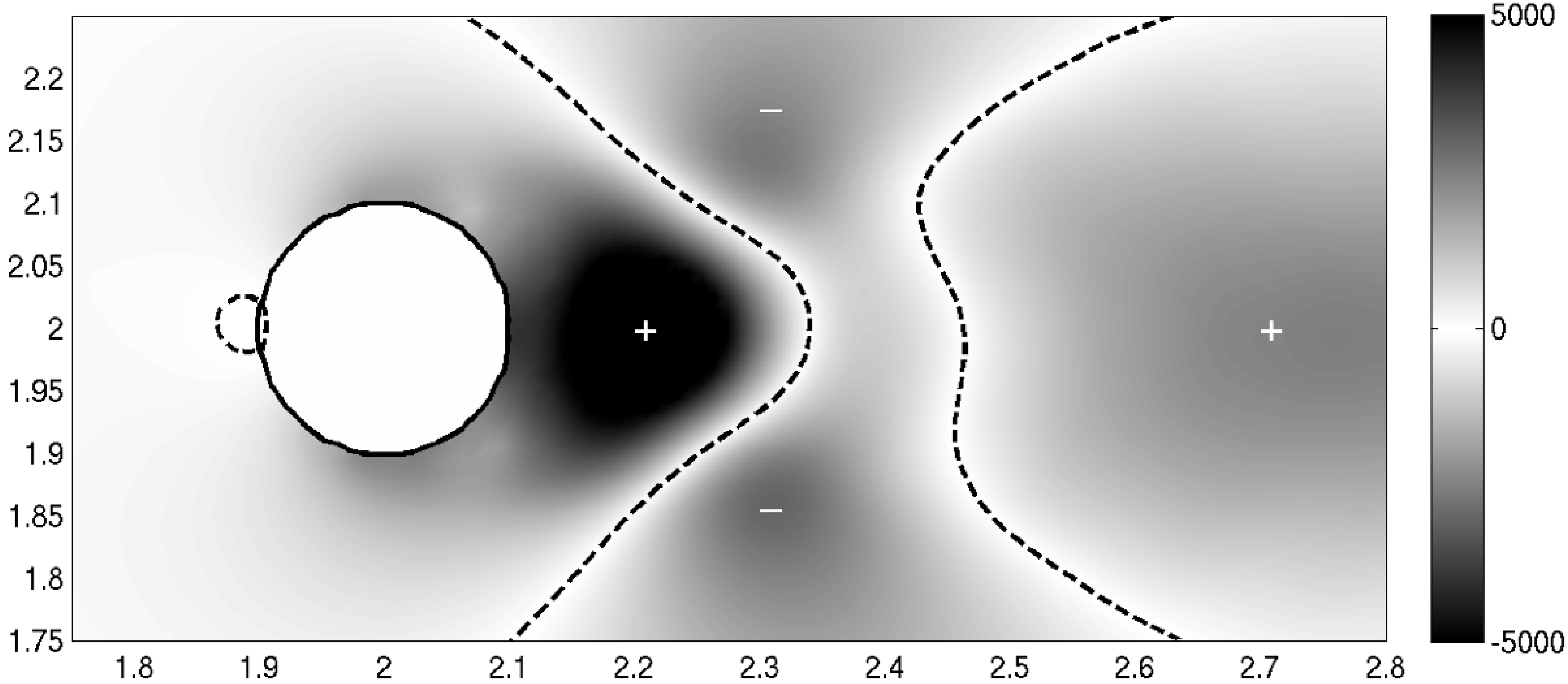
	Cd	Cd'	Cl'	St
Case 1 	1.3689 (1.39;1.356)	0.0274	0.4381	0.199 (0.199;0.198)
Case 2 	3.1464	0.1943	1.1376	0.1946
Case 3 	1.3035	0.0207	0.3839	0.1916
Case 4 	1.2109	0.012	0.3008	0.1661

(Bergmann et al. Phys. Fluids 2005 ; He et al J. Fluid Mech. 2000)

Aerodynamic perf.(ctd.)

	Cd	Cd'	Cl'	St
Case 1 	ref	ref	ref	ref
Case 2 	+130%	+608%	+160%	-2.21%
Case 3 	-4.78%	-24.54%	-12.37%	-3.71%
Case 4 	-11.54%	-56.09%	-31.34%	-16.53%

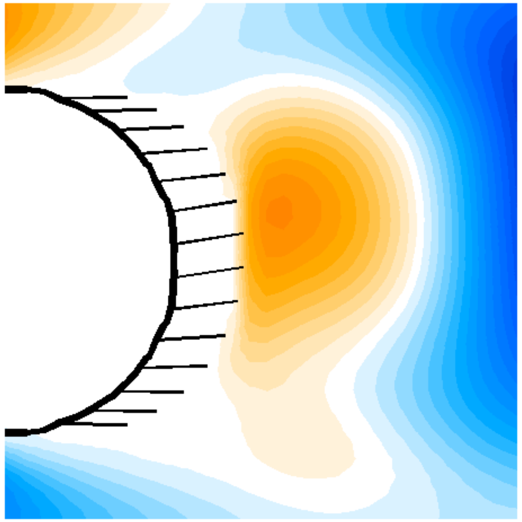
Physical mechanism



Difference of time-averaged pressure field

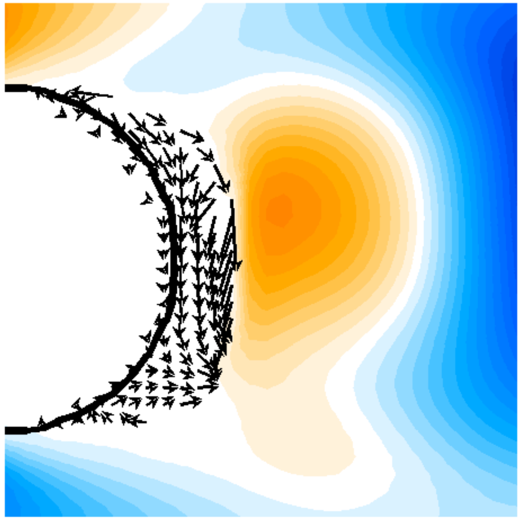
<P with hair>-<P ref>

Physical mechanism



Contours of vertical velocity

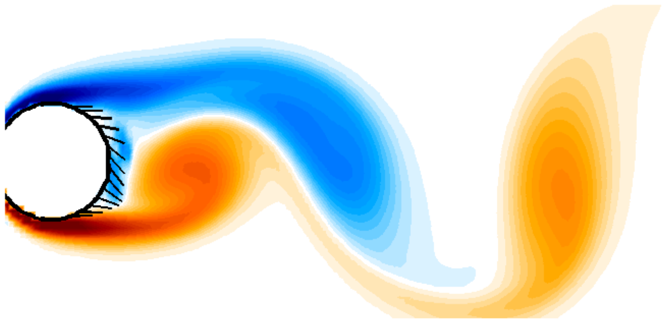
Movements of *reference* cilia



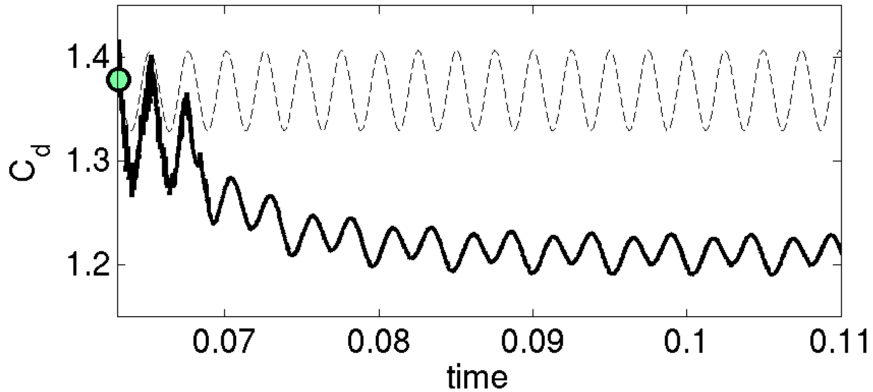
Contours of vertical velocity

Force field

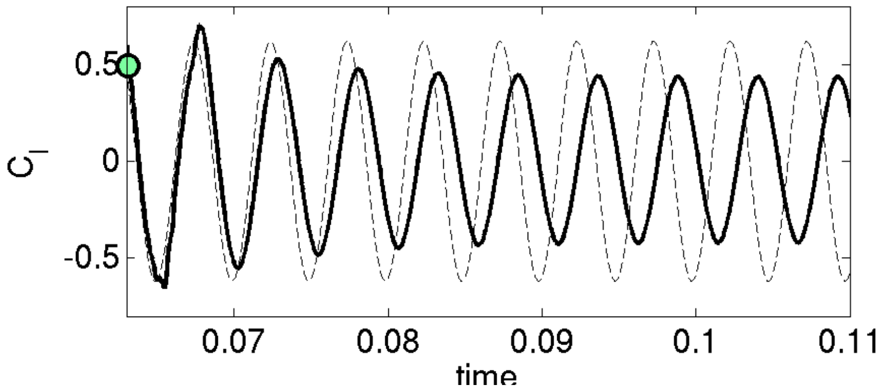
The hairy layer counteracts flow separation



Optimal **self-adaptive hairy layer**



15% drag reduction

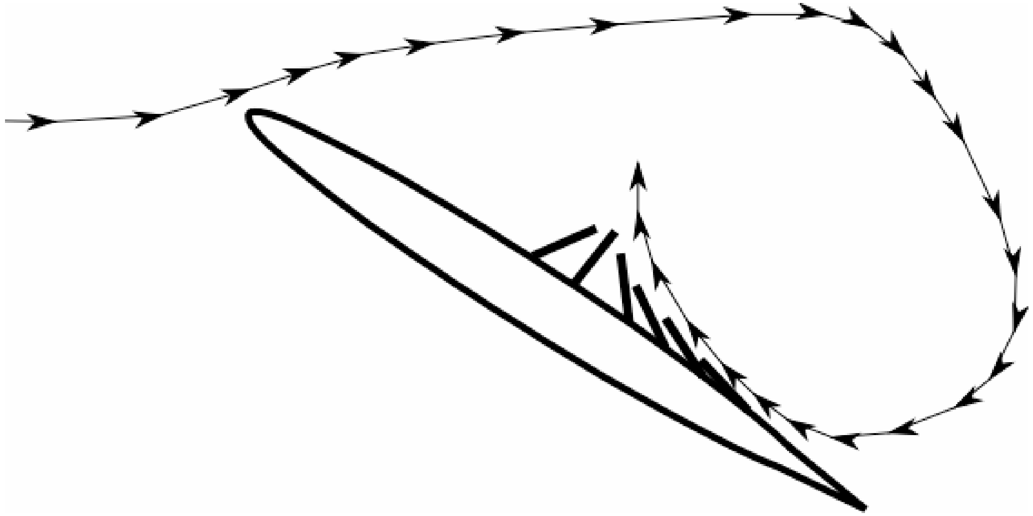


40% reduction in lift fluctuations

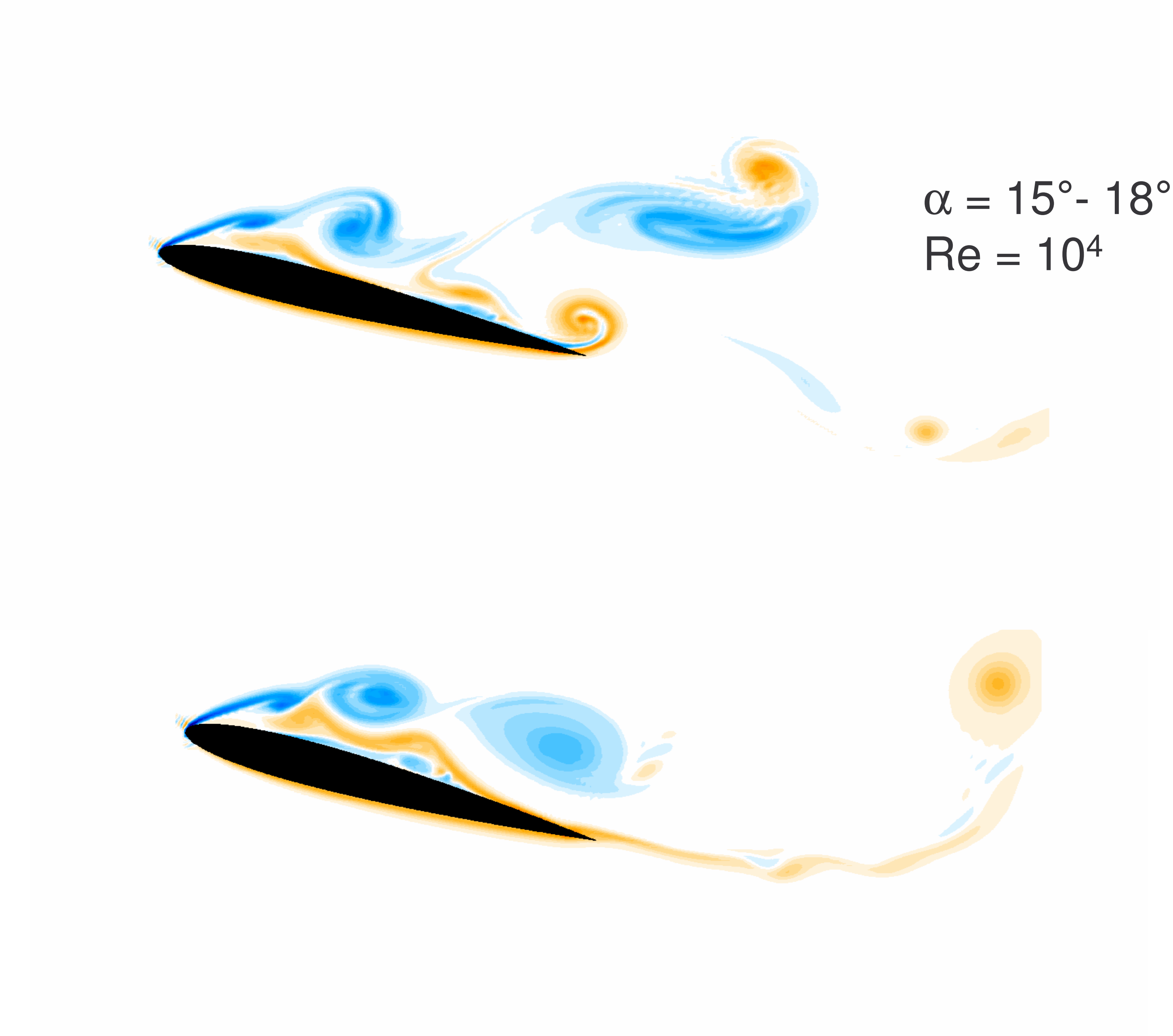
Reducing pressure drag:

- ✓ Simulations show a reduction of pressure drag on a cylinder for a unsteady laminar flow (Re = 200).
- ✓ The motion of the hairy structures can improve aerodynamic performances
- ✓ The structural parameters of the actuators have been optimised
- ✓ Immediate perspectives concern flexible rods and turbulent configurations; possible applications to small underwater vehicles and to UAV/MAV (in the aeronautical field)

and now, what about lift?



Consider a hairfoil: the control elements (the *feathers*) must be placed in the position of largest *sensitivity* to achieve an effect



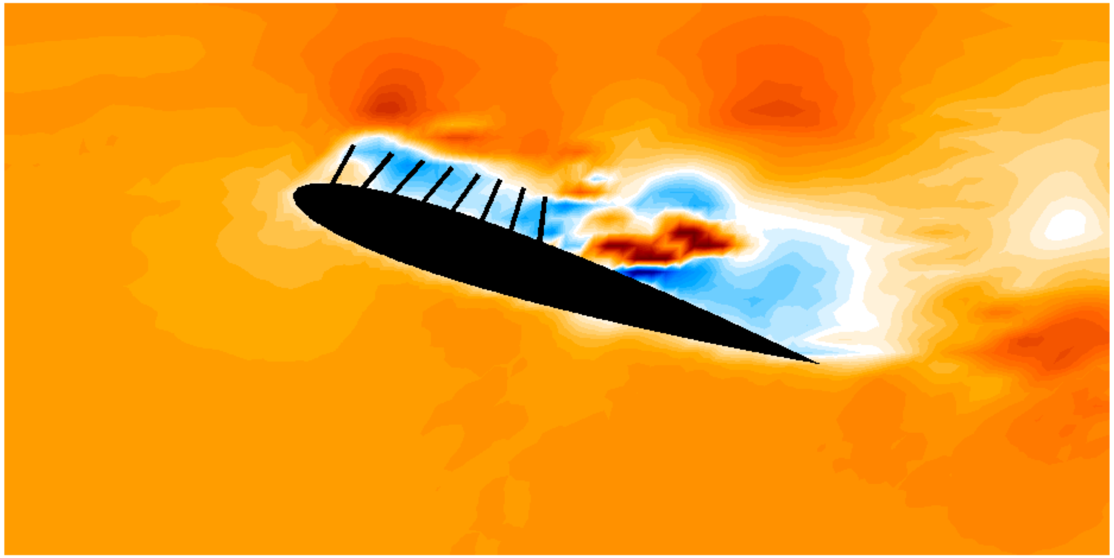
α = 15°- 18°
Re = 10^4

Preliminary runs with control elements going from 0.12 chord to 0.95 chord

$\alpha = 15°$ $\langle C_D \rangle = 0.284$ $\langle C_L \rangle = 0.579$

$T_{fluid} = 0.5\ T_{structure}$	*+ 1.35%*	*- 13%*
$T_{fluid} = T_{structure}$	+ 2 %	- 10%
$T_{fluid} = 2\ T_{structure}$	+ 3%	- 9%
$T_{fluid} = 4\ T_{structure}$	- 0.2 %	+ 2.5%
$T_{fluid} = 8T_{structure}$	-7 %	- 11%

Results are similar when $\alpha = 18^o$, except that now $\langle C_L \rangle$ increases the most for $T_{fluid} = 2\ T_{structure}$



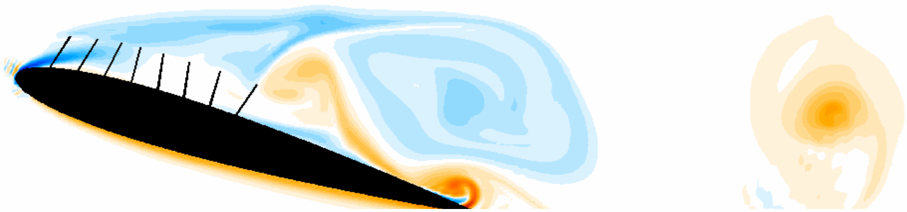
The amplitude of the oscillations decreases (the system's stability improves) as $T_{structure} \nearrow$

$(i.e. \quad m \nearrow \quad l \nearrow \quad K_r \searrow)$

A parametric resonance must be triggered to optimise the response of the system

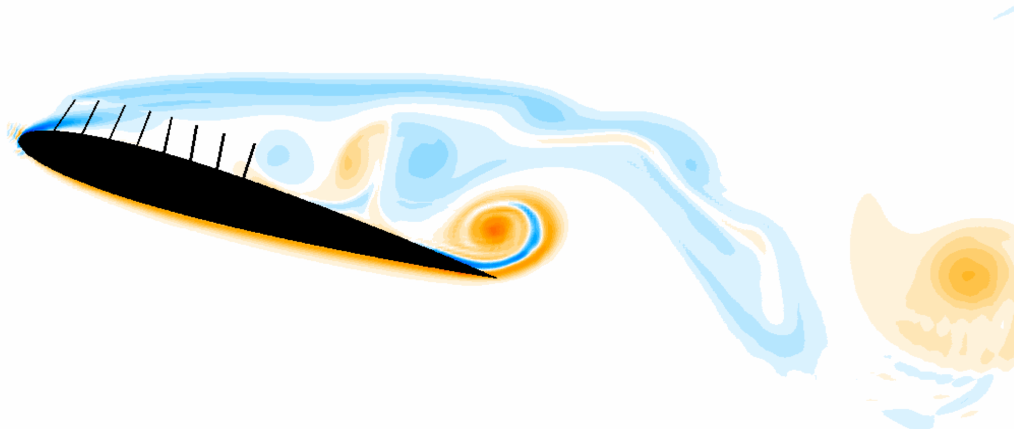
Control elements within 0.06 chord and 0.45 chord

$T_{structure} \approx T_{fluid} = 1.53$

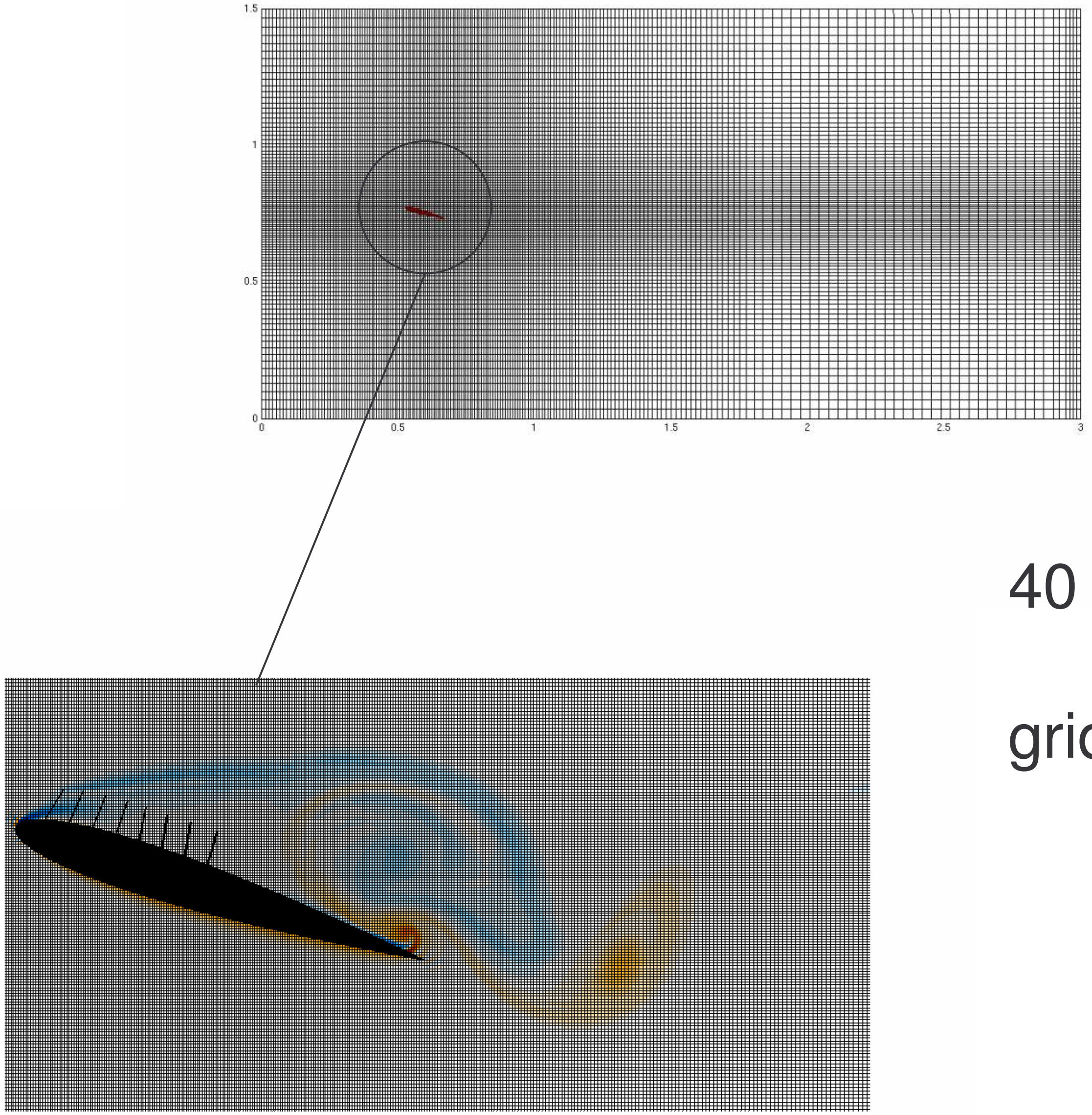


α = 18°

$\rho_{feathers}$ = 890 Kg/m^3 (keratin)



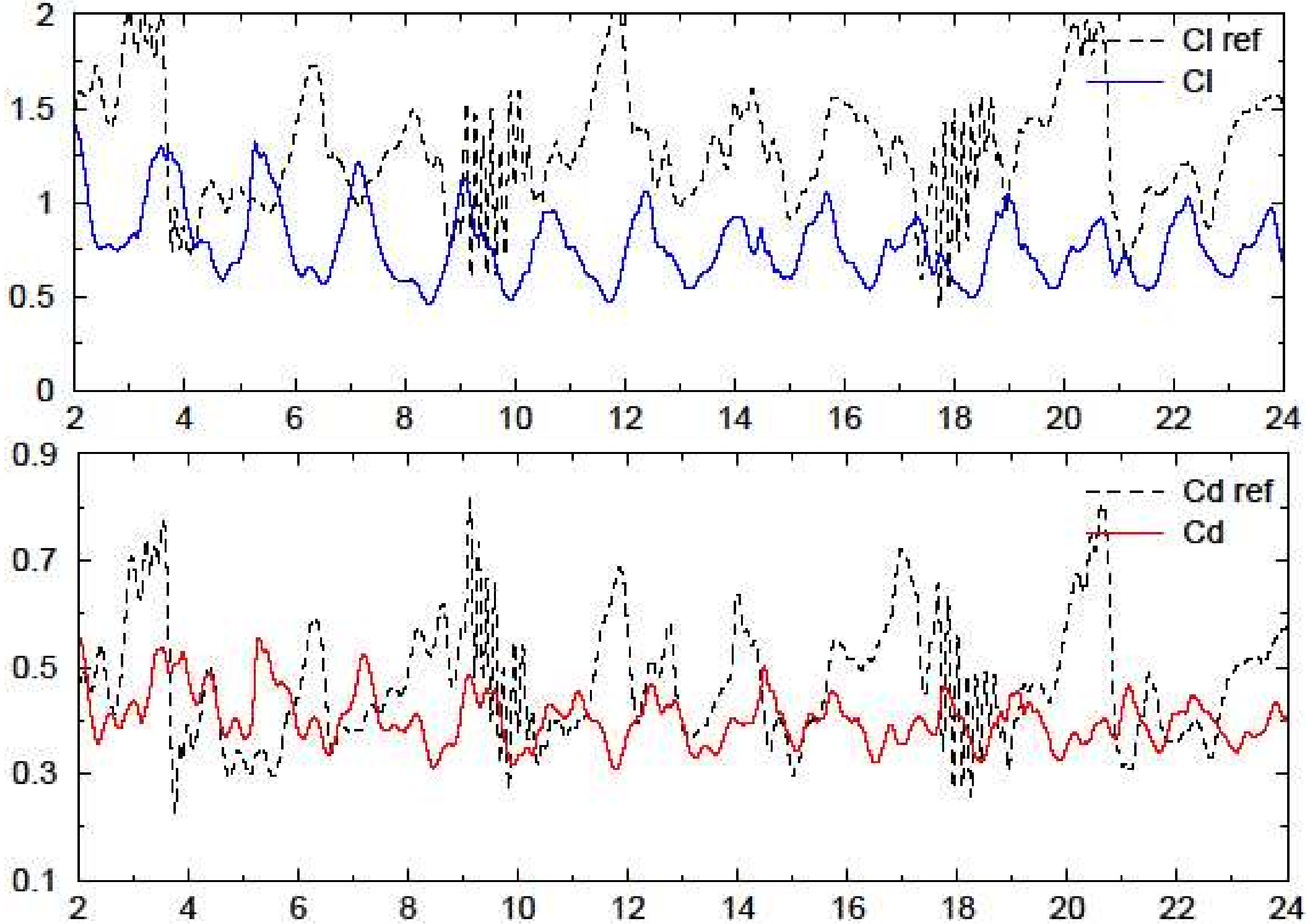
α = 18°



40 chords x 20 chords

grid: 1200 x 600

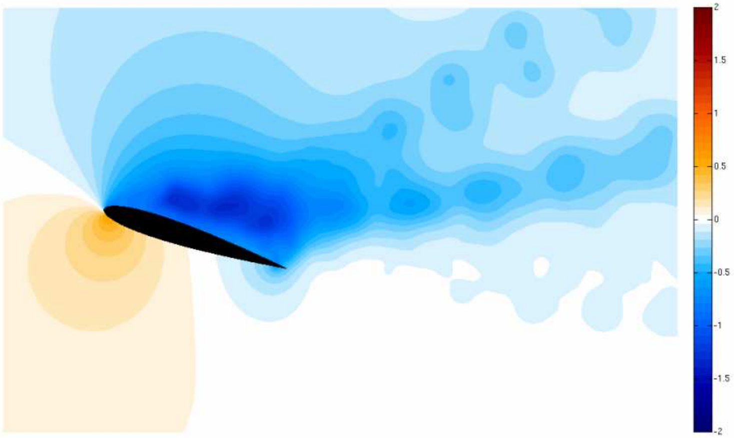
Drag reduction by about 15%
Lift reduction by about 40%
About 60% reduction in the amplitude of the oscillations



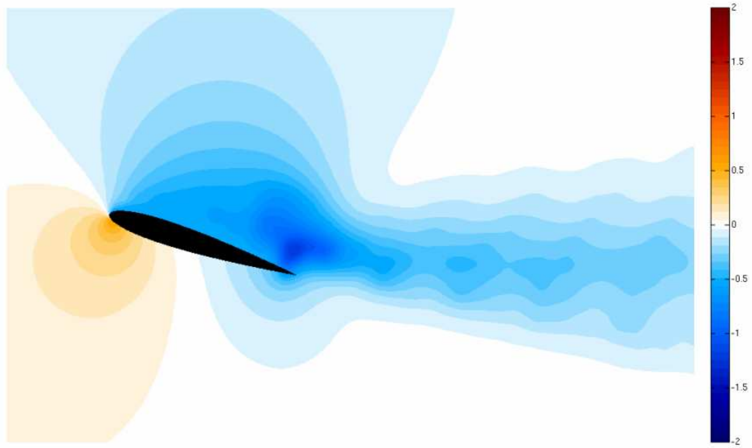
$\langle C_l \rangle = 1.27$
$\langle C_l \rangle = 0.76$

$\langle C_d \rangle = 0.475$
$\langle C_d \rangle = 0.402$

Mean pressure field



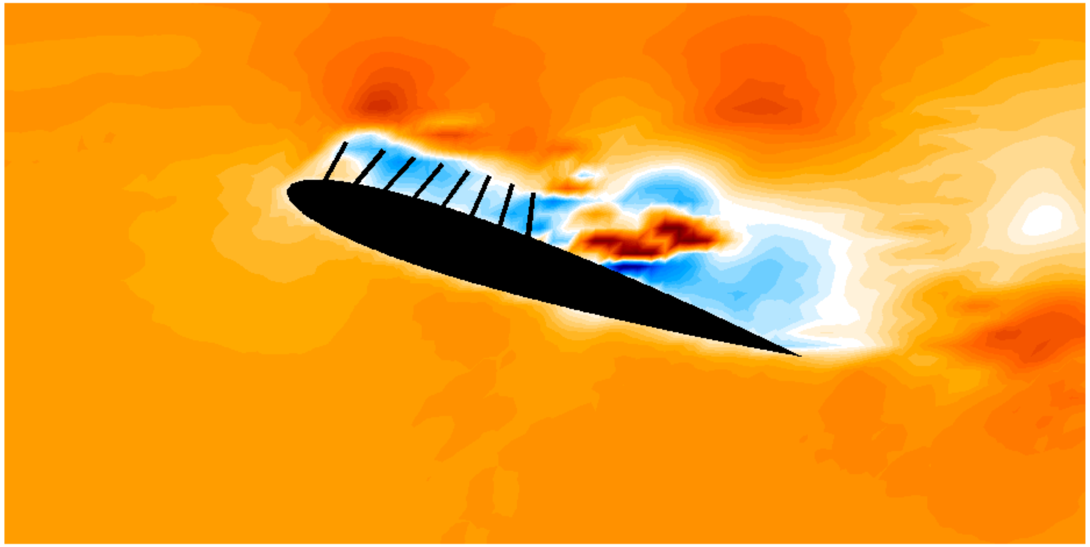
no control



with control

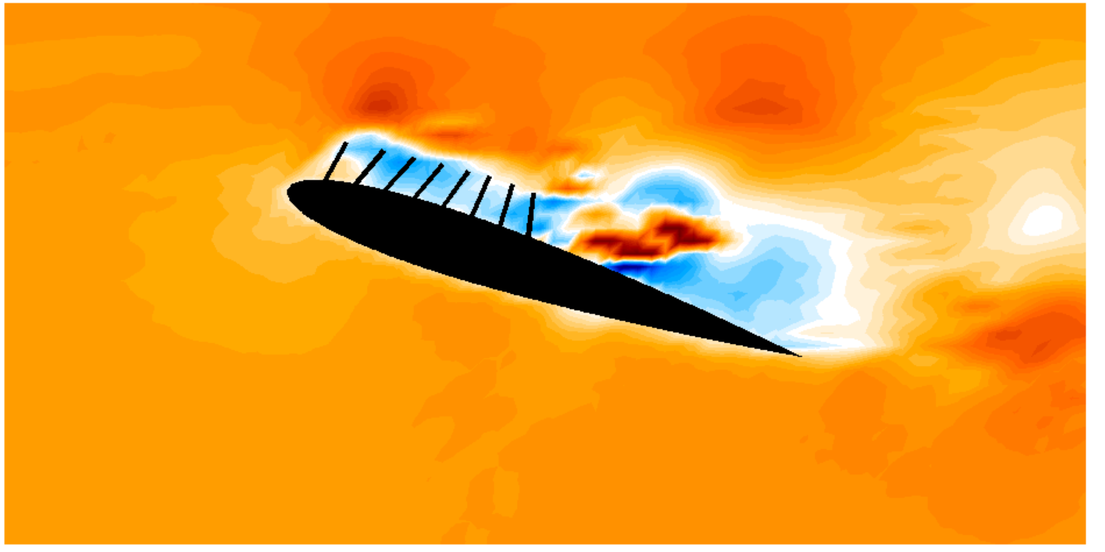
Issues left:

- extend the parametric search
- link the properties of the optimised structures to those of a suitable material
- wind tunnel/water channel tests (Ch. Brücker, U. Freiberg)



Engineering perspectives

MAV/UAV
Car, trucks and trains – underwater vehicles
Wind turbines
Hydraulic machines (cavitation)
Sound mitigation



Paleontological perspective

Dinosaur ancestry of birds: could the “feathery” dinousars discovered in the Liaoning province fly?

Fluid mechanics could say something on the role of those protofeathers …

Ajit Ninan, 2009