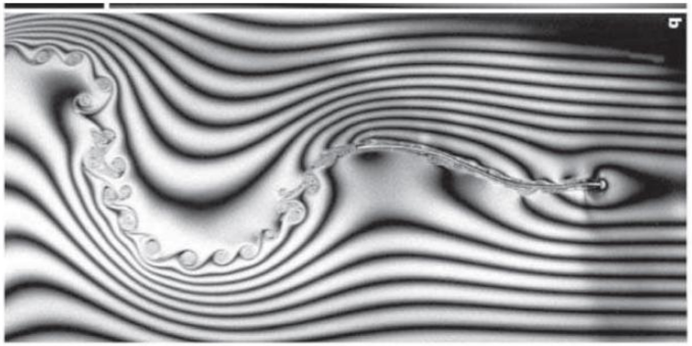
Spontaneous Symmetry Breaking of a Hinged Flapping Filament Generates Lift

A. Bottaro (DICCA, University of Genova)

S. Bagheri *(KTH, Stockholm)*
A. Mazzino *(DICCA, Genova)*

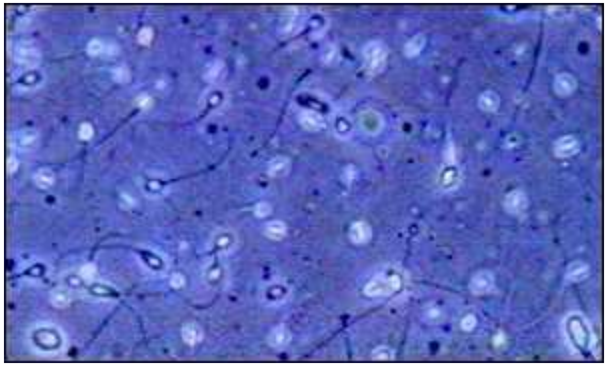
J. Favier *(AMU, Marseille)*
A. Dauptain *(CERFACS, Toulouse)*

EPFL, Nov. 27, 2012



Advantage/disadvantage of *passive flexible* parts/appendages in animal propulsion?

Re << 1, micro-organisms use *non-reciprocal* waves to move (no inertia → symmetry under time reversal)



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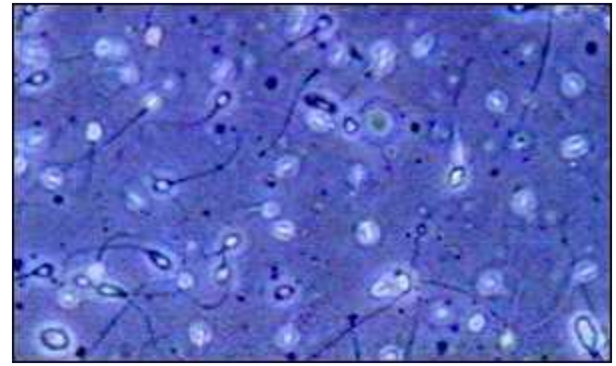

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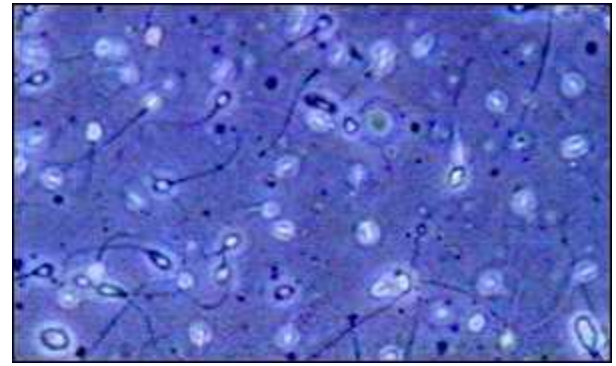
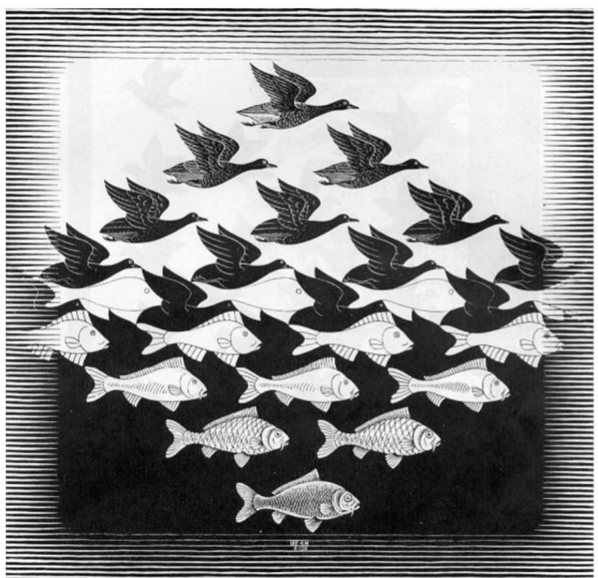


Re >> 1, birds/fish use *reciprocal flapping* for lift and/or propulsion



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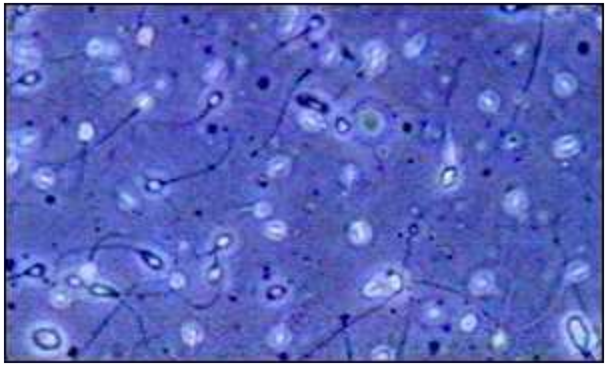

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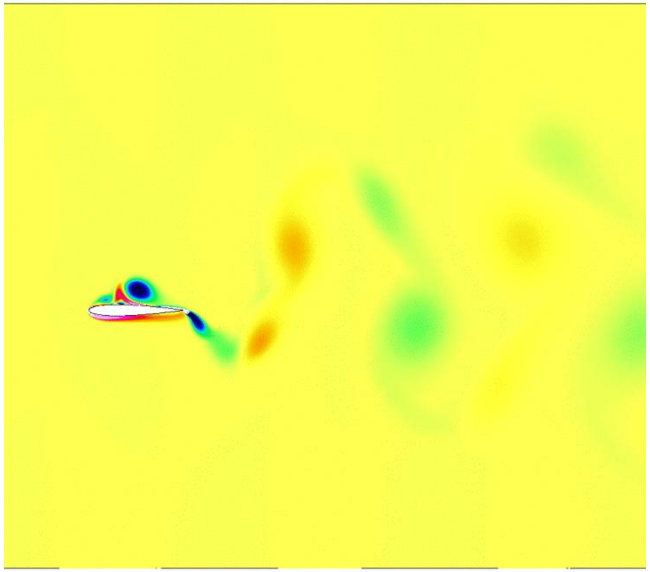
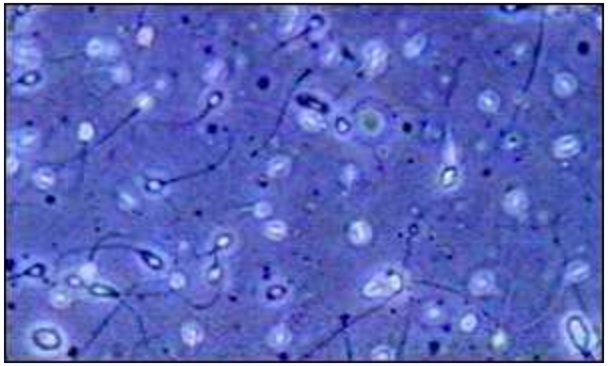


Heaving, rigid, symmetric foil (thrust)

(inverted von Karman vortex street)

Re << 1, micro-organisms use *non-reciprocal waves* to move (no inertia → symmetry under time reversal)



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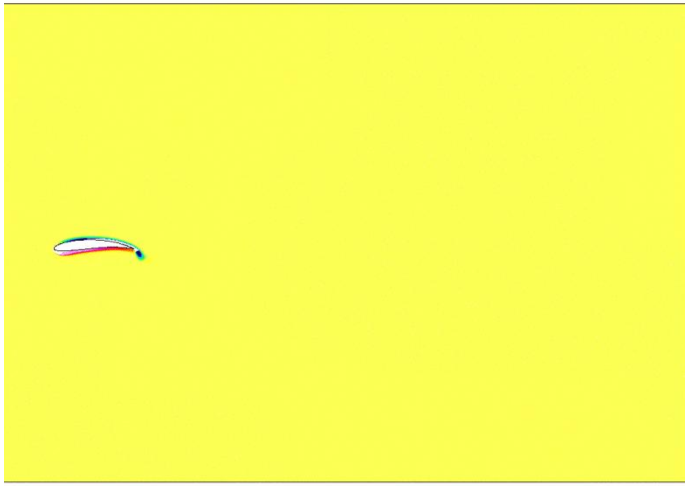
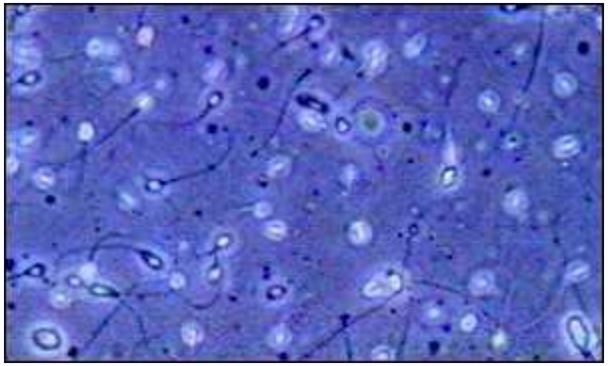


Heaving, rigid, cambered foil (plus lift)

Re << 1, micro-organisms use *non-reciprocal waves* to move (no inertia → symmetry under time reversal)



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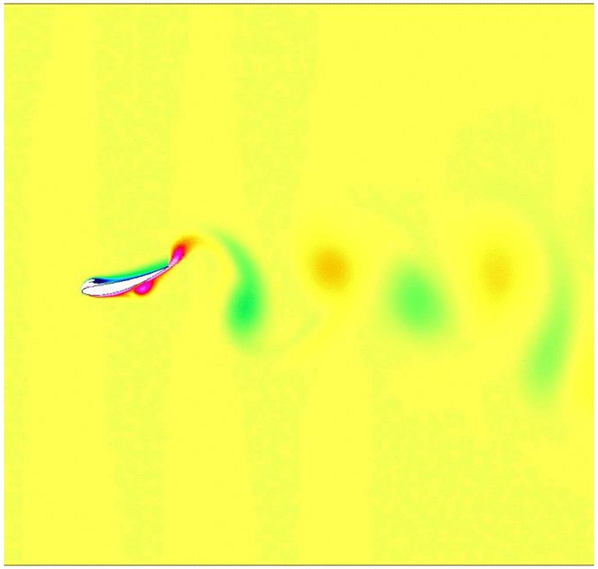

Heaving, *flexible*, cambered foil (plus …)

J. Guerrero, PhD Thesis, 2009, UNIGE

Some animals live between these worlds: **Re ≈ 10 - 100** (and present flexible appendages)

Clione Antarctica (“sea slug”), a marine mollusc which switches mobility strategy with adulthood:

rowing cilia → flapping wings

Childress & Dudley, *JFM* 2004

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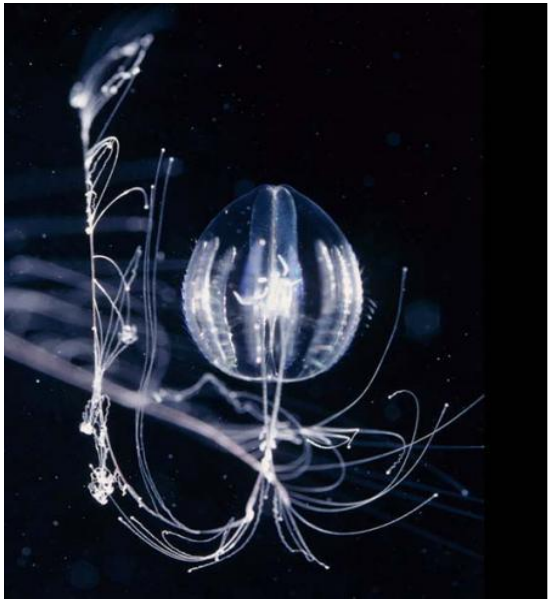

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Pleurobrachia Pileus (comb-jelly), a member of the Phylum Ctenophora which moves in water thanks to the rythmic beating of eight rows of cilia.

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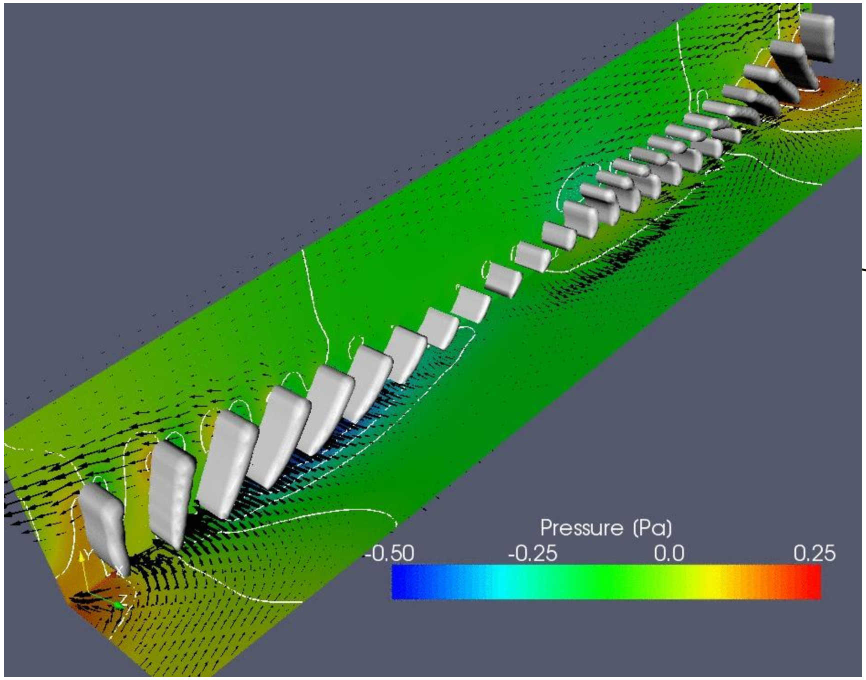
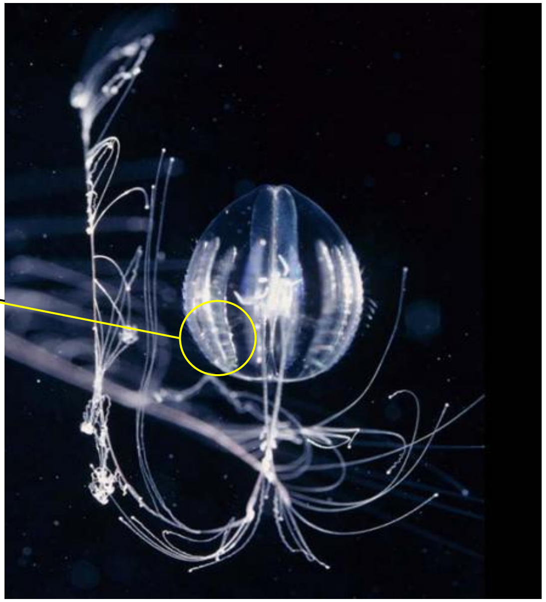
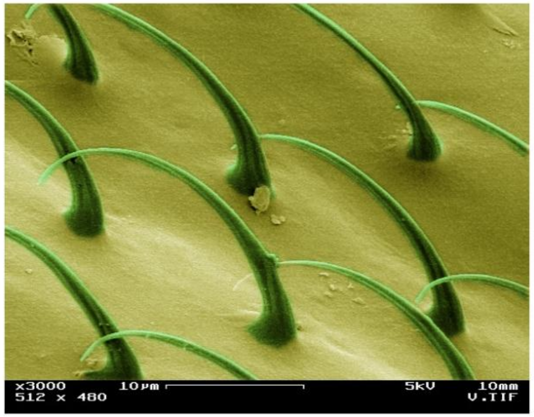


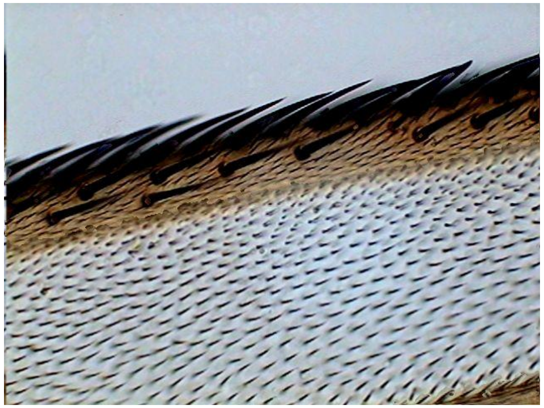


Pleurobrachia Pileus (comb-jelly), a member of the Phylum Ctenophora which moves in water thanks to the rythmic beating of eight rows of cilia

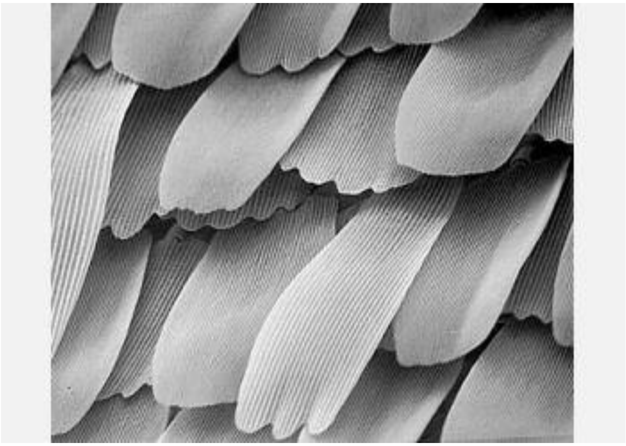
Dauptain, Favier & Bottaro, *JFS* 2008



fly



mosquito



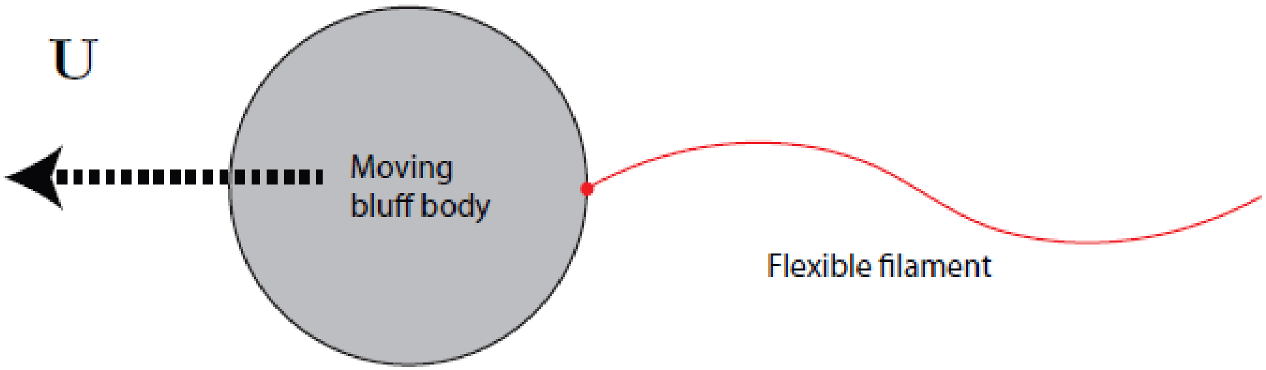
butterfly

“pop-up” feathers

In Nature “rough” is rule, not exception …

Is there some dramatic change in the interaction between a “free” body and a fluid as Re $\nearrow$

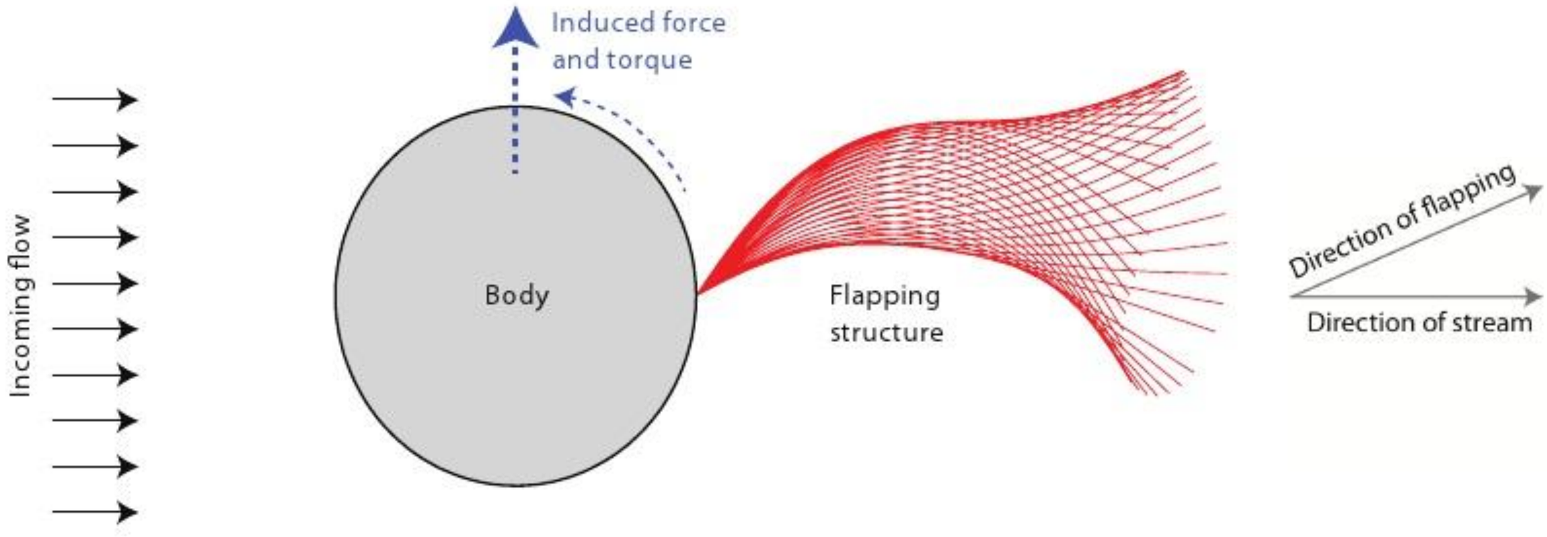
What is the role of apparently *inert* filaments/cilia/tentacles/scales/feathers?



Symmetry breaking!

Filament flap asymmetrically:

- induced force and torque
- reduced drag



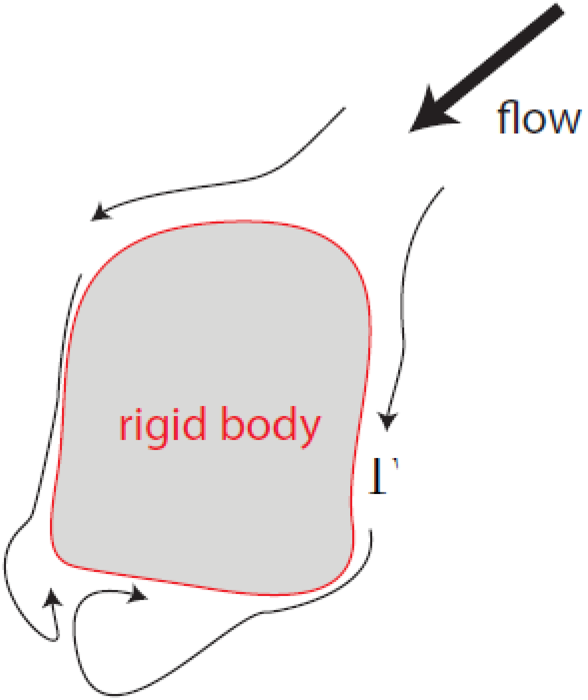
The numerical method

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u}$$

$$\nabla \cdot \mathbf{u} = 0$$

No-slip

$$\mathbf{u} = 0 \qquad \text{on} \quad \Gamma$$



The numerical method: IBM

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\nabla p + \frac{1}{Re}\nabla^2\mathbf{u} + \int_\Gamma \mathbf{f}(\zeta)\delta(\mathbf{x}-\zeta)\,\mathrm{d}\zeta$$

$$\nabla\cdot\mathbf{u} = 0$$

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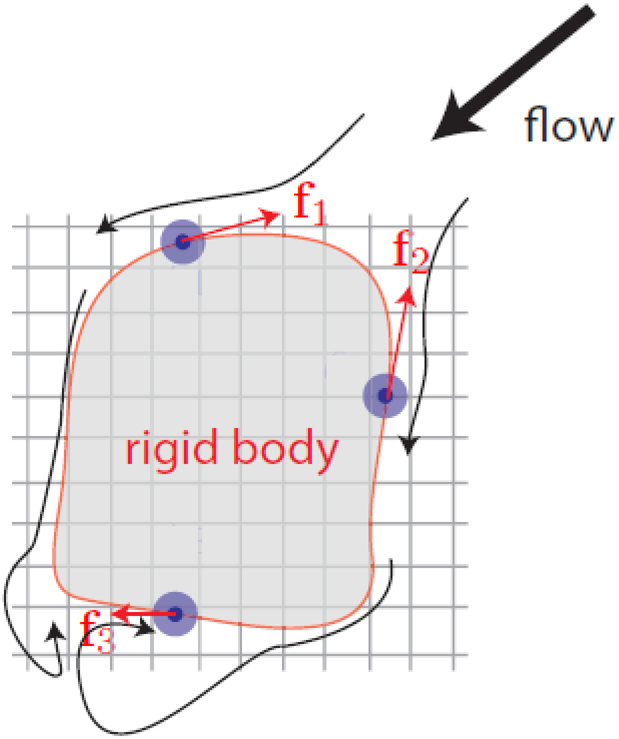


Flow field: Eulerian grid
Boundary: Lagrangian points
Boundary force to enforce
no-slip condition
Projection method
(Taira & Colonius, *JCP* 2005)

The numerical method: IBM + the flexible filament

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} + \int_\Gamma \mathbf{f}(\zeta)\delta(\mathbf{x} - \zeta)\, \mathrm{d}\zeta$$

$$\nabla \cdot \mathbf{u} = 0$$

No-slip

$\mathbf{u}(\Gamma) = \dot{\zeta}$ $\zeta = \zeta(s,t)$ *s*: arclength

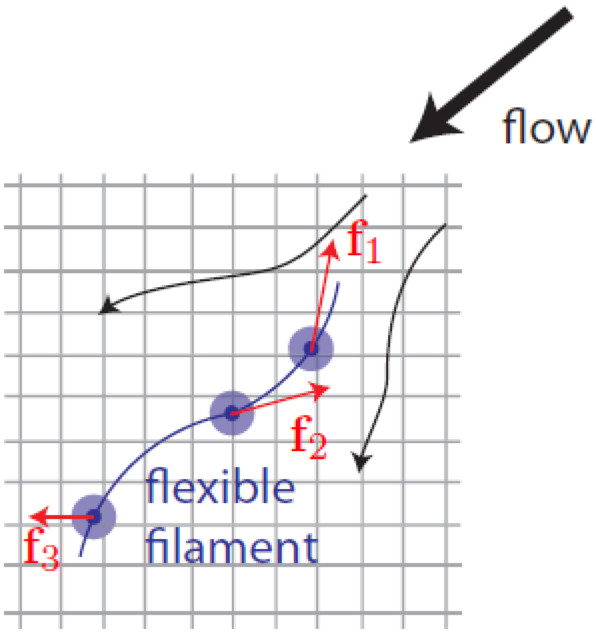
Filament dynamics : Euler-Bernoulli

$$\rho_s \ddot{\zeta} = \partial(T\hat{\tau}) - B\partial^2(C\hat{n}) + \mathbf{f}$$

Inertia

Tensile force

Bending force

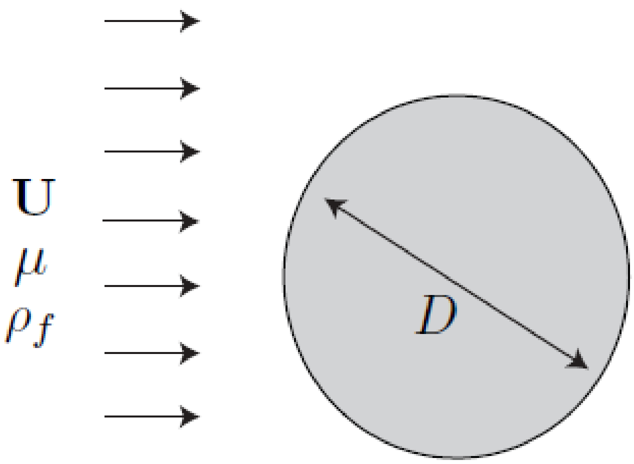


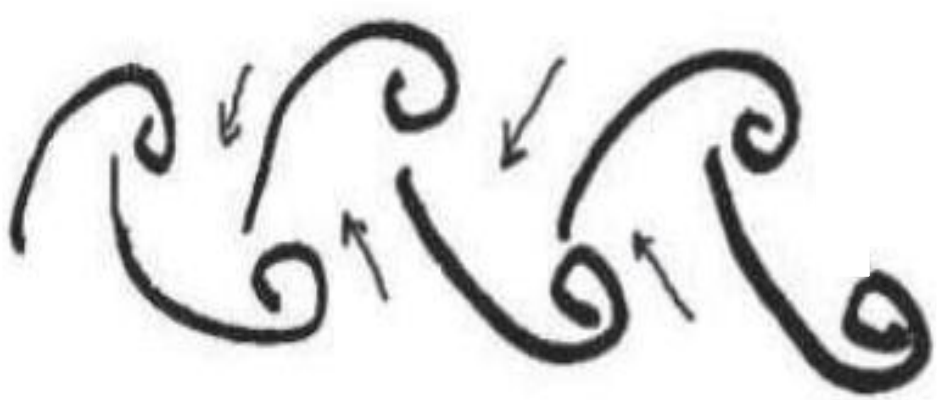
Peskin, *Acta Numerica* 2002
Kim & Peskin, *PoF* 2007

The cylinder alone: symmetric wake

– Reynolds number $Re = \dfrac{\mathbf{U} D \rho_f}{\mu}$

– Vortex shedding for $Re > Re_c$ with frequency f_c





(classical von Karman vortex street)

Williamson, *ARFM* 1996

The filament alone: symmetric flapping

– Reynolds number

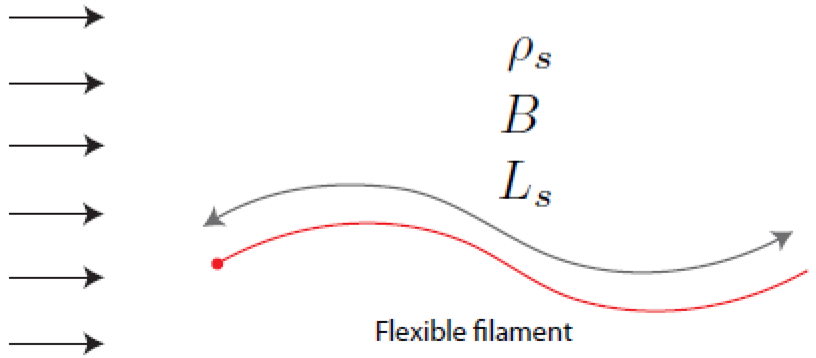
$$Re = \frac{\mathbf{U} L_s \rho_f}{\mu}$$

– mass

$$R_1 = \frac{\rho_s}{\rho_f L_s}$$

– rigidity

$$R_2 = \frac{B}{\rho_f U^2 L_s^3}$$

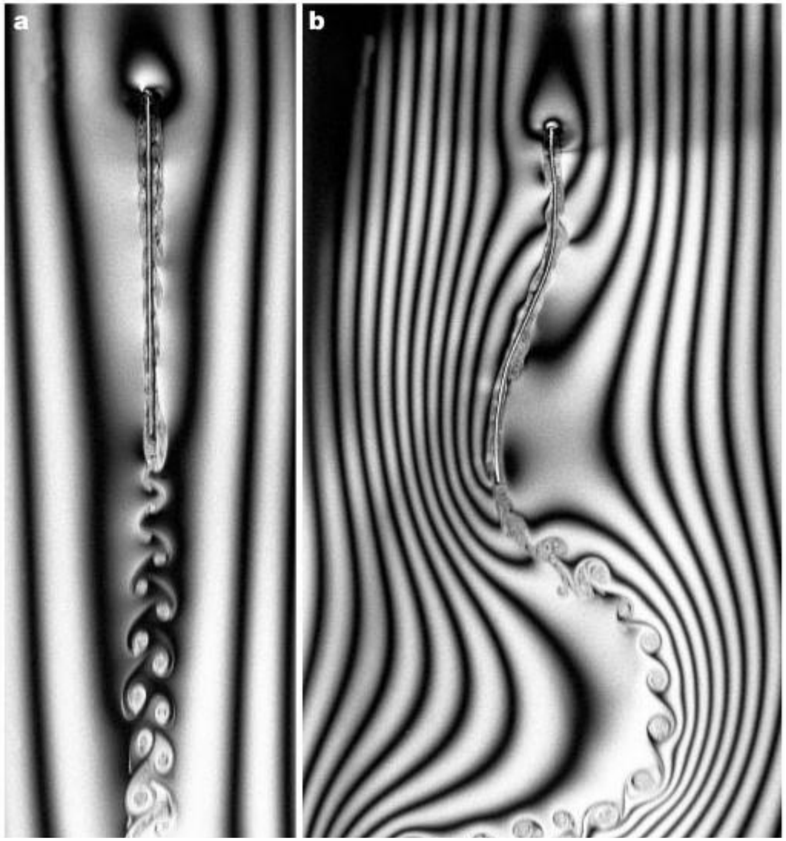


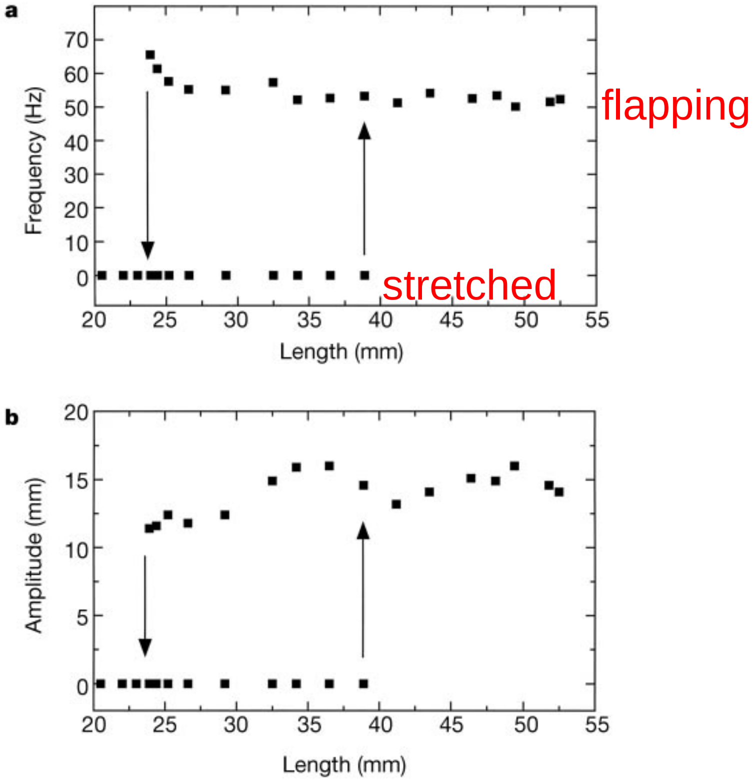
μ
ρ_f
$\mathbf{U}$

$T = \zeta_{ss} = \zeta_{sss} = 0$
@ s = L_s (filament free end)

$\zeta = \zeta_{ss} = 0$
@ s = 0 (hinged position)

The filament alone (soap film experiments)





Zhang, Childress, Libchaber & Shelley, *Nature* 2000
Shelley & Zhang, *ARFM* 2011

The filament alone (theory)

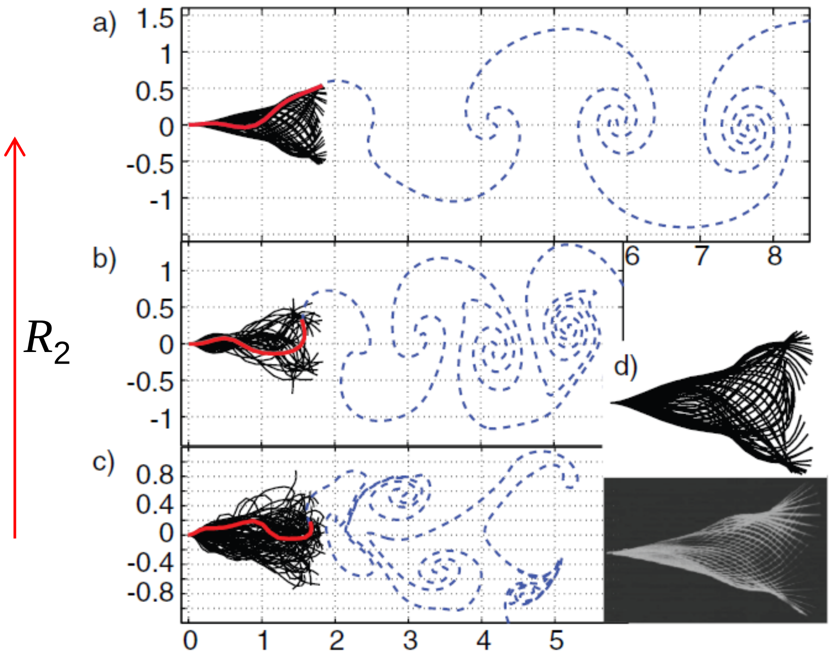


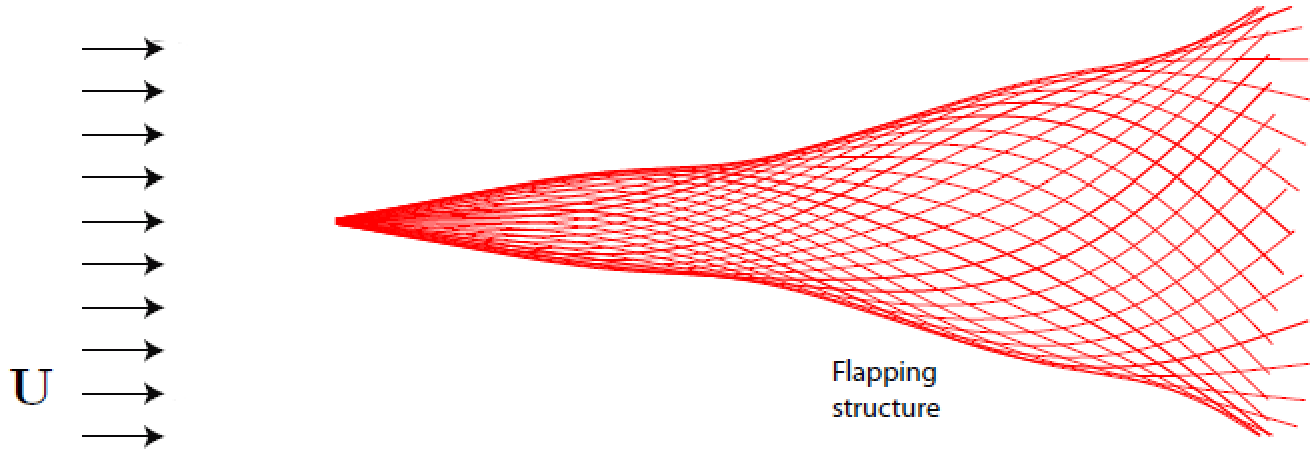
FIG. 2 (color online). Snapshots of the flag for fixed mass ($R_1 = 0.3$) and decreasing rigidities R_2. (a) The observed flapping mode at $R_2 = 0.014\,45$, about a factor of 2 below the critical $R_2 = 0.0262$; (b) a higher energy flapping mode for $R_2 = 0.0138$; (c) a chaotic flapping mode at $R_2 = 0.0025$. (d) Comparison of experimental flag snapshots in [18], Fig. 12b, with model shapes. In both cases $R_1 = 0.37$ (see text for R_2).

Inviscid flow theory: vortex sheet (filament) + shed free vortex sheet → Biot-Savart integral (for velocity ⊥ to the filament) + Euler equation

Alben & Shelley, *PRL* 2008

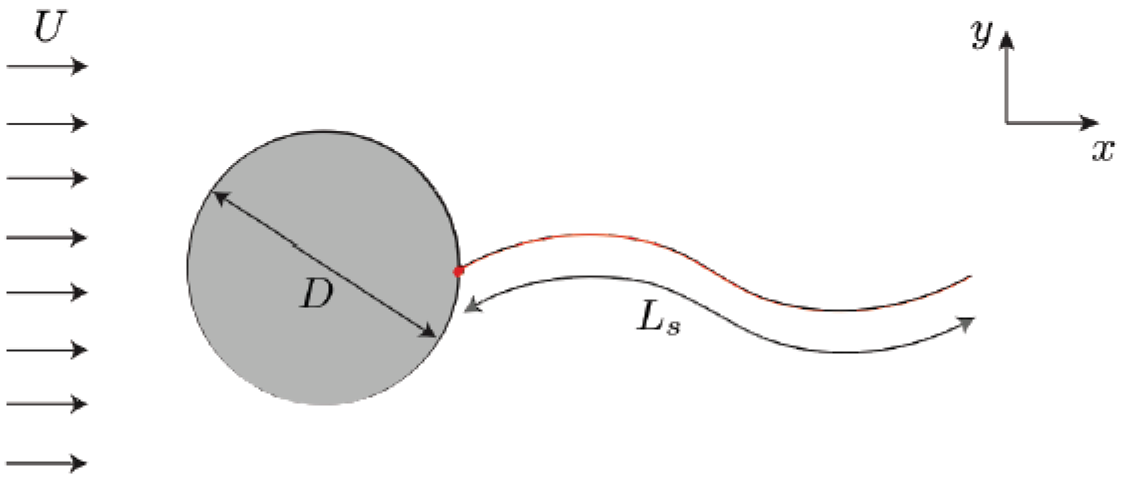
The filament alone (numerical simulations)

- Flapping when $Re > 10^3 \quad R_1 > 0 \quad R_2 < R_{2,c}$

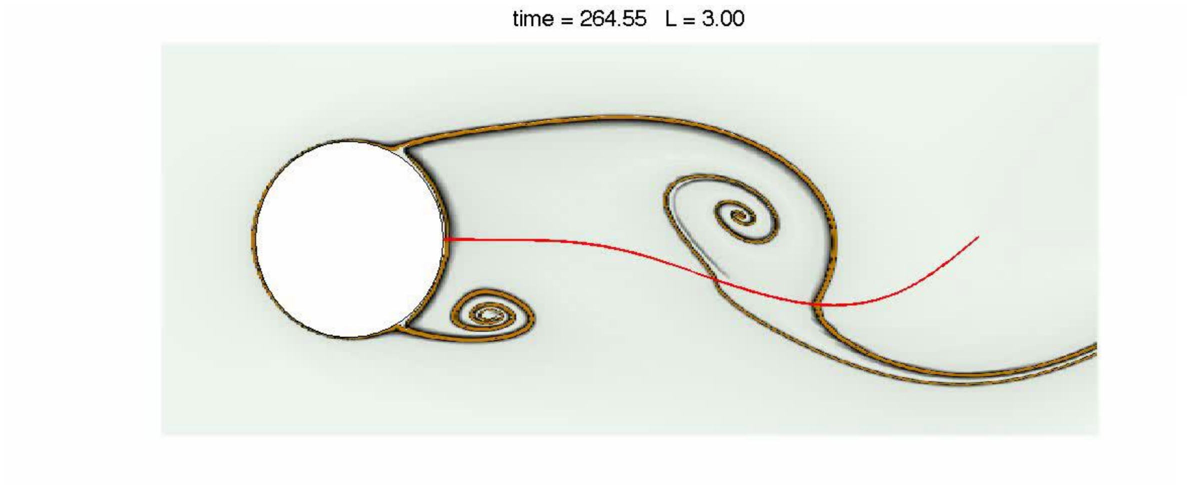


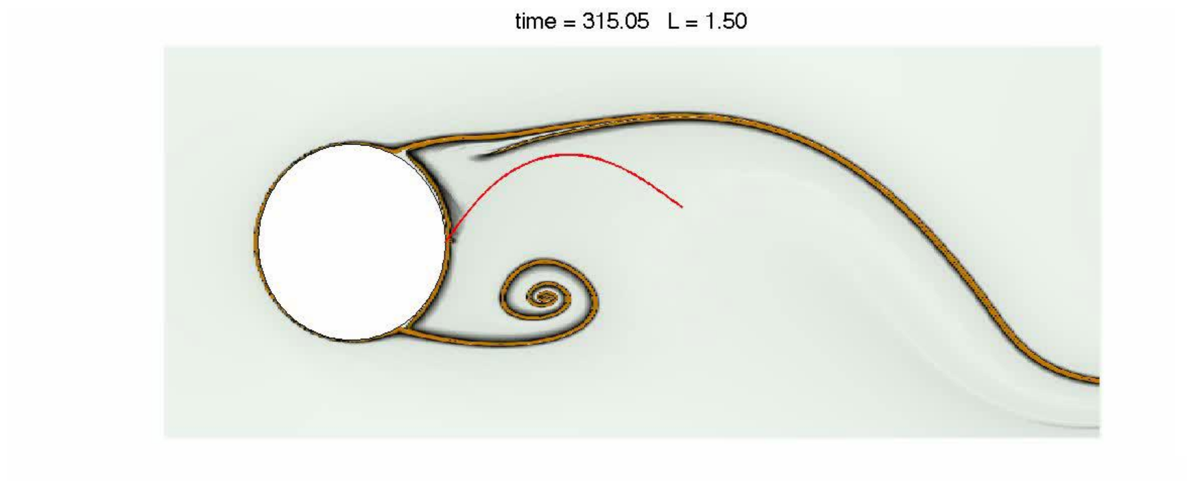
Cylinder + filament: something happens …

$$L = \frac{L_s}{D}, \quad Re = \frac{UD}{\nu} \quad R_1 = \frac{\rho_s}{\rho_f D} \quad R_2 = \frac{B}{\rho_f U^2 D^3},$$



Re = 100, R_1 = 0.1, R_2 = 0.005, L = 3 and L = 1.5





Bagheri, Mazzino & Bottaro, *PRL* 2012

$L = 3$

$\langle C_D \rangle = 1.28$ (drag)

$\langle C_L \rangle = 0$ (lift)

$\langle C_q \rangle = 0$ (torque)

$L = 1.5$

$\langle C_D \rangle = 1.32$

$\langle C_L \rangle = 0.18$

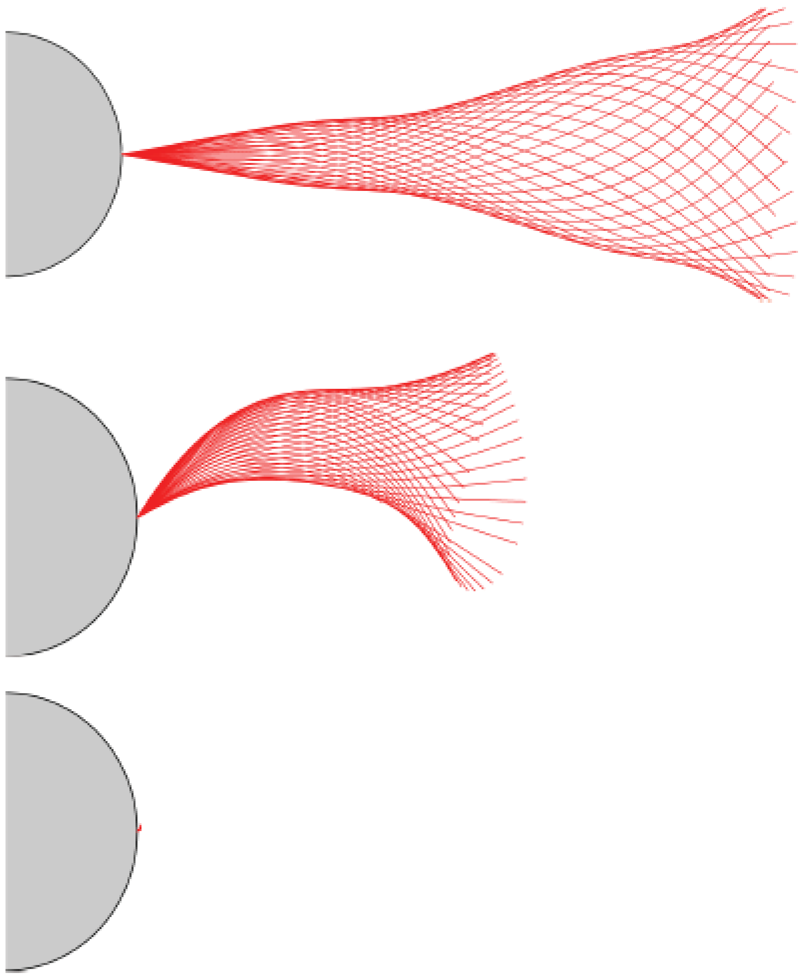
$\langle C_q \rangle = 0.01$

$L = 0$

$\langle C_D \rangle = 1.36$

$\langle C_L \rangle = 0$

$\langle C_q \rangle = 0$



L	R_2	C_d	C_l	C_q	f_c
0.0	-	1.36 ± 0.01	0.00 ± 0.34	0.00	0.164
3.0	0.005	1.28 ± 0.06	0.00 ± 0.23	0.00	0.157
1.5	0.005	1.32 ± 0.08	0.18 ± 0.28	0.01	0.159
1.5	0.100	1.23 ± 0.05	0.21 ± 0.24	0.02	0.145

increasing R_2 → increased rigidity of the structure

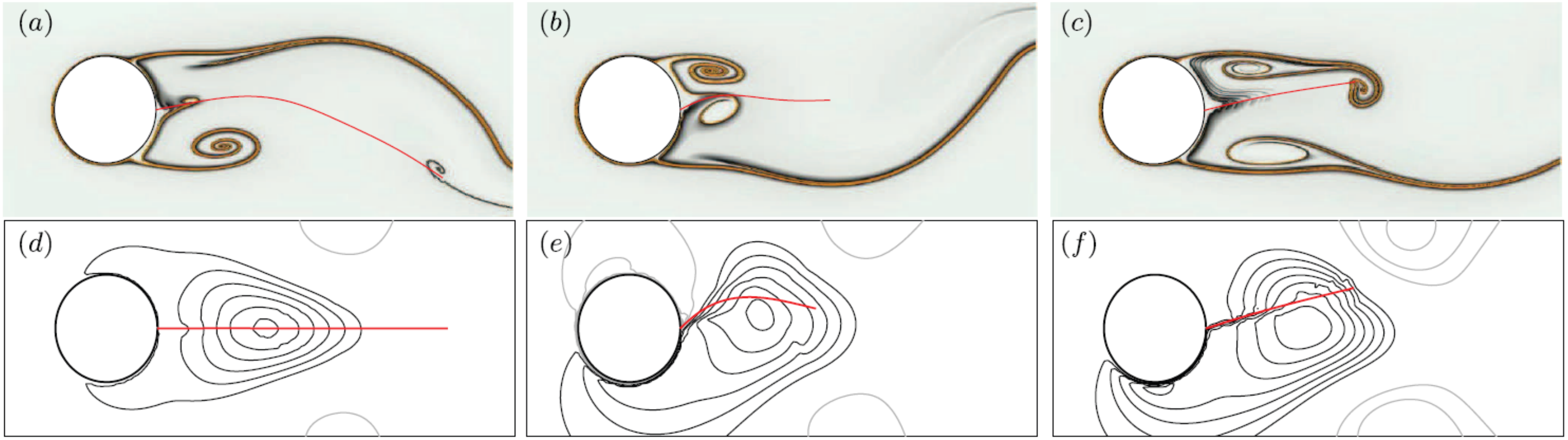
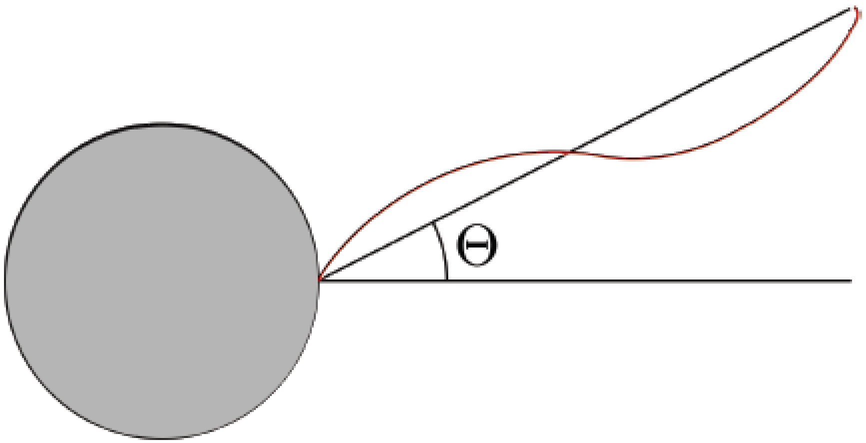


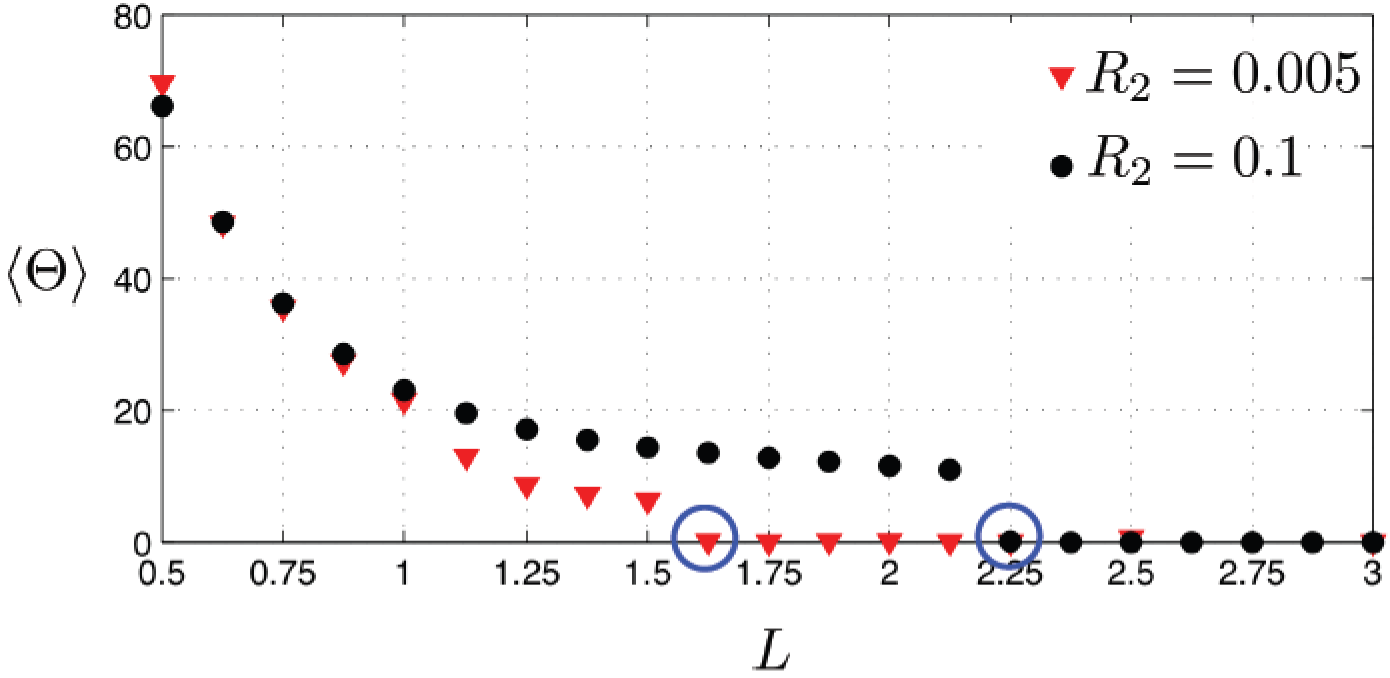
FIG. 4 (color online). Left, center, and right columns correspond, respectively, to long/flexible (case ①), short/flexible (case ②) and short/stiff filaments (case ③). Top row shows instantaneous snapshots of the maximum value of the FTLE and filament position (solid line). Bottom row shows mean filament position (solid line) and mean pressure distortion. The latter is defined as the difference between the time-averaged pressure field with and without the filament. Positive (negative) distortions are plotted with solid black (gray) contour lines; positive pressure distortion in the leeward side of the cylinder signals reduced pressure drag, while asymmetric distortion with respect to the x axis indicates that a net y force is generated.

Choice of observable

- Angle of horizontal line & line connecting filament tail



- Consider 2 cases
  - Rigid filament: $R_2 =$ 0.1
  - Flexible filament: $R_2 =$ 0.005



- Bifurcation: $L_c = 1.6$ (flexible filament)

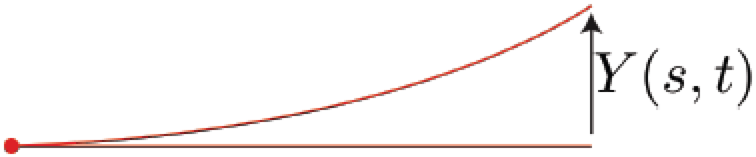
  $L_c = 2.25$ (rigid filament)

A symmetry-breaking bifurcation occurs when vortices and structures resonate …

Beam equation

- Equation governing unforced beam

$$R_1 Y_{tt} + R_2 Y_{ssss} = 0$$



- Eigenfrequency

$$f_s = \sqrt{\frac{R_2}{R_1 L^4}}$$

Resonance condition

- Free vibrations of filament f_s
- Vortex shedding frequency f_c
- If $f_s \ll f_c$ filament with slow reaction time
- If $f_s \gg f_c$ filament reacts instantaneously
- Thus $f_s \sim f_c$ separates two different regimes

$$\boxed{L_r = \left(\frac{R_2}{R_1 f_c^2}\right)^{1/4}}$$

– Energy $$E = \frac{1}{2}\int_0^L R_1|\,\dot{\zeta}\,|^2 + R_2|\,\zeta_{ss}|^2\,ds$$

– Rescaled with filament density and length

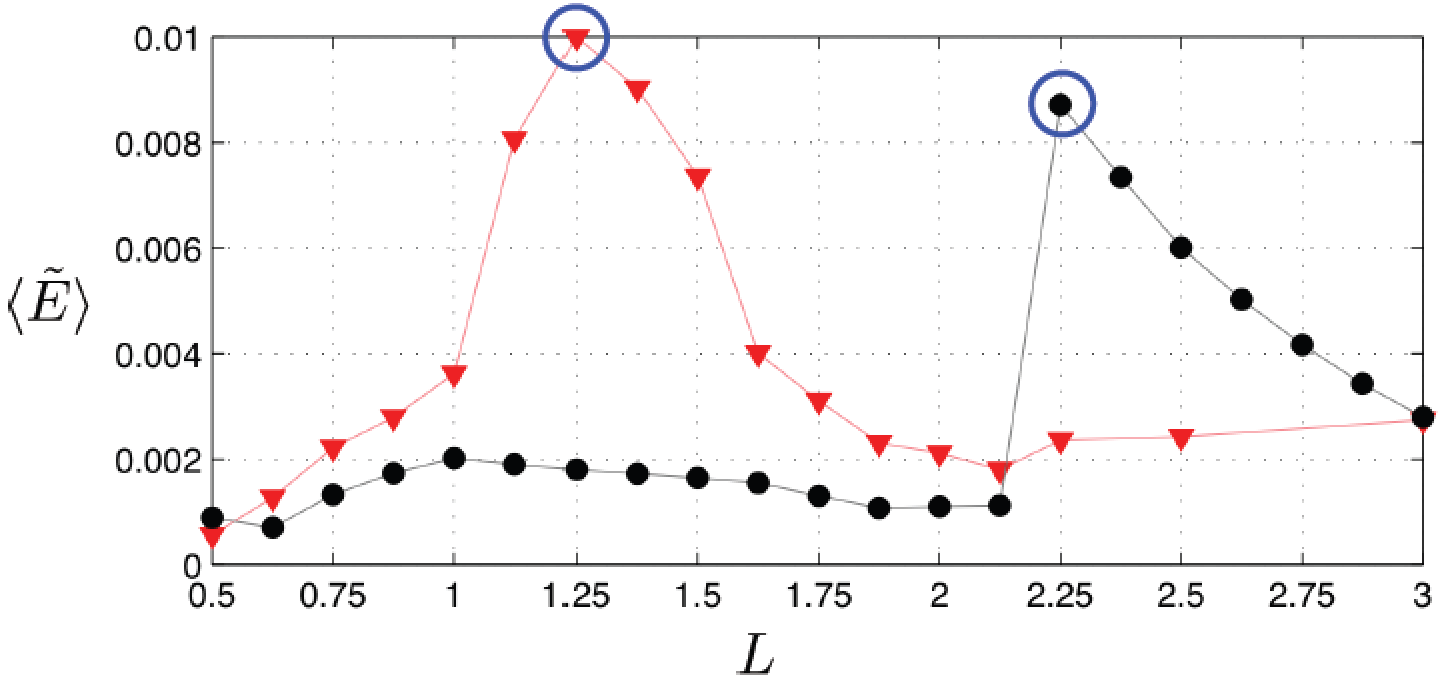
$$(\rho_f, D) \to (\rho_s, L_s)$$

– Flapping synchronized with vortex shedding, time scale

$$U/D$$

→ rescaled non-dimensional filament energy $\tilde{E} = \frac{R_1}{L^3}E$

Resonance



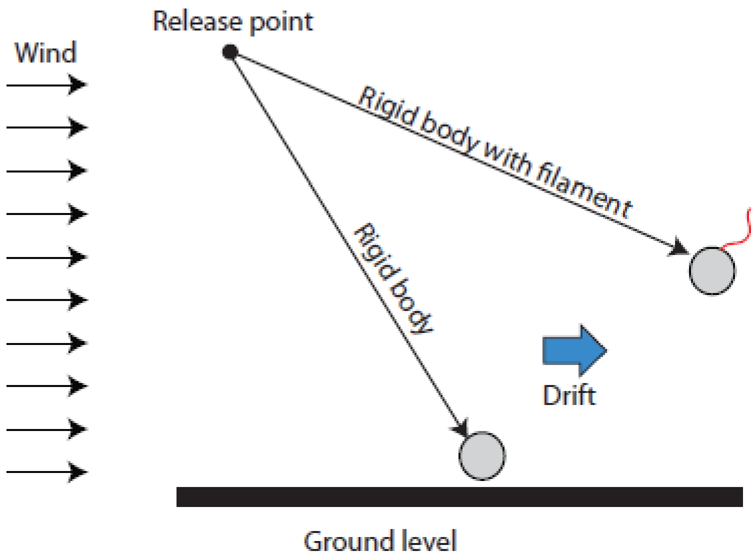
- Resonance: $L = 1.25$ (flexible)
  $L = 2.25$ (rigid)

Resonance

	Resonance (theoretical)	Resonance (computed)	Bifurcation (computed)
Flexible	1.25	1.25	1.6
Rigid	2.6	2.25	2.25

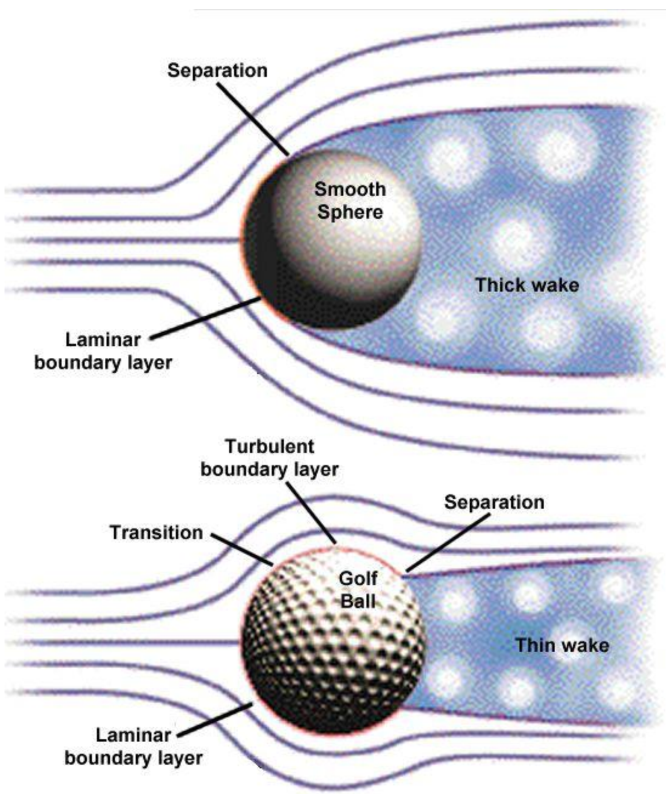
Can filaments increase drift?

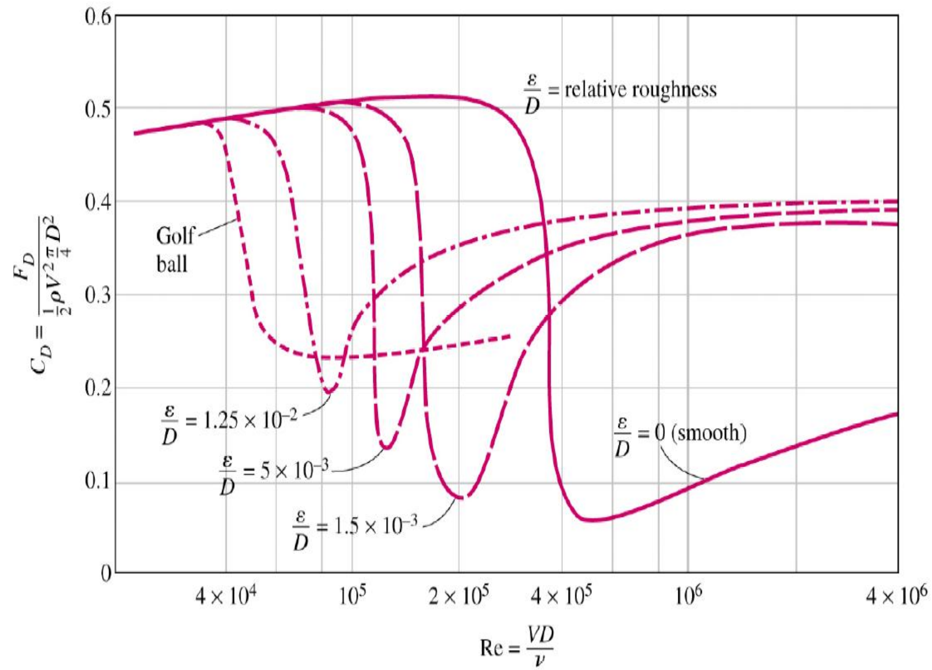
- Efficient wind-borne seed dispersal
  - Side force due to symmetry breaking may increase drift



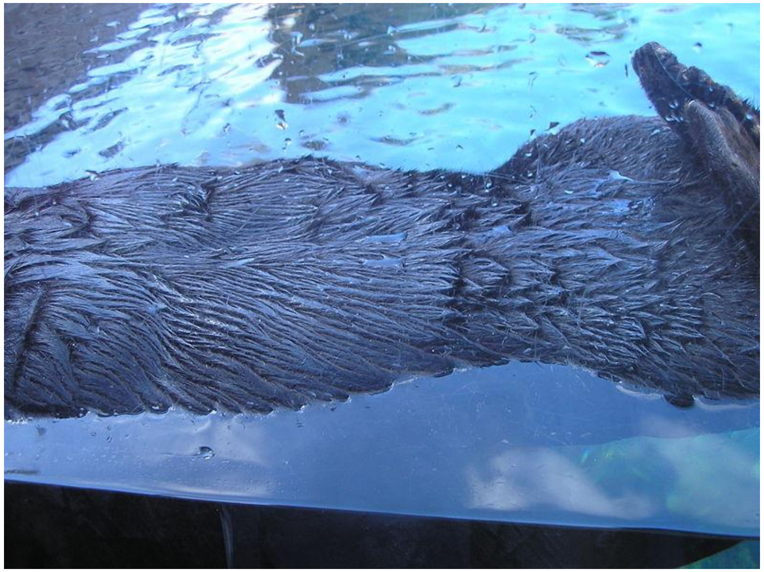
(Burrows, *New Phytol.* 1975)

Can filaments reduce drag "optimally" (because of compliance) as opposed, i.e., to the (sub-optimal) pressure drag reduction of golf balls?





How to model a passive, compliant hairy/feathery coating?

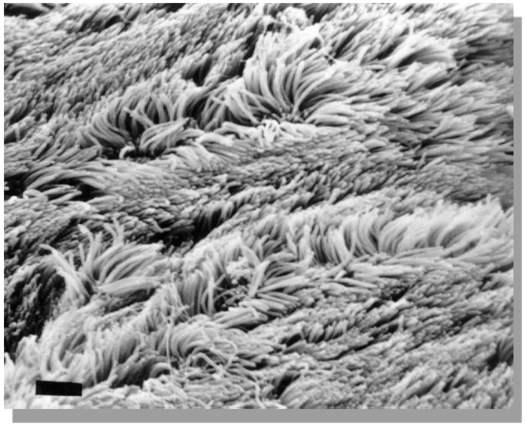


sea otter

egret

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

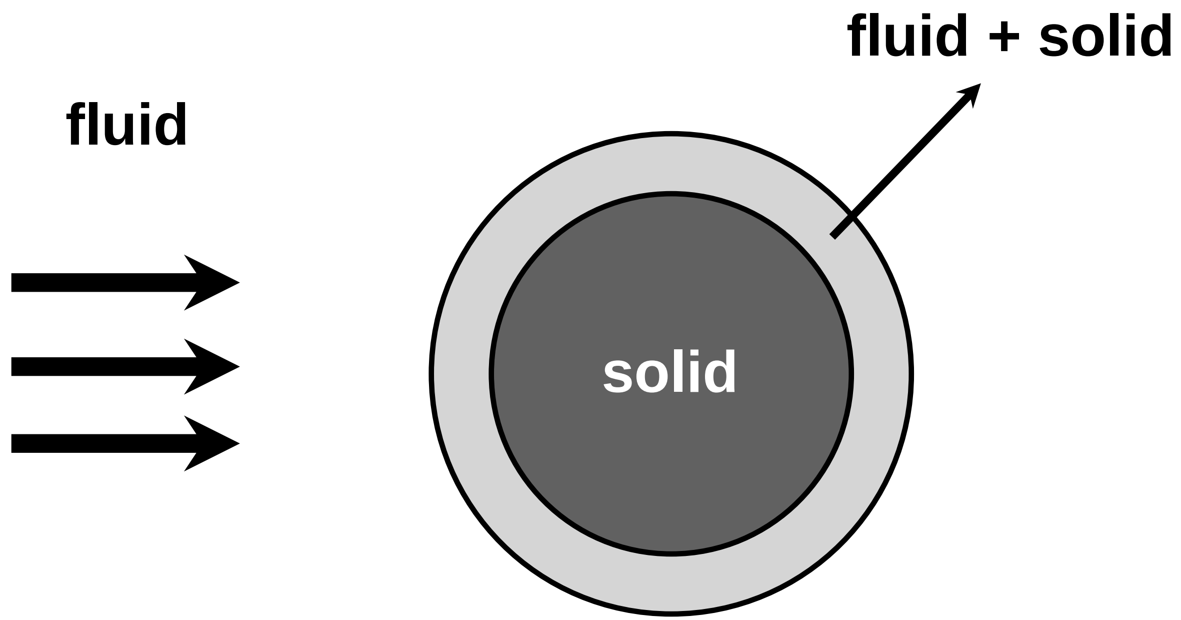
Numerical challenges



- **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

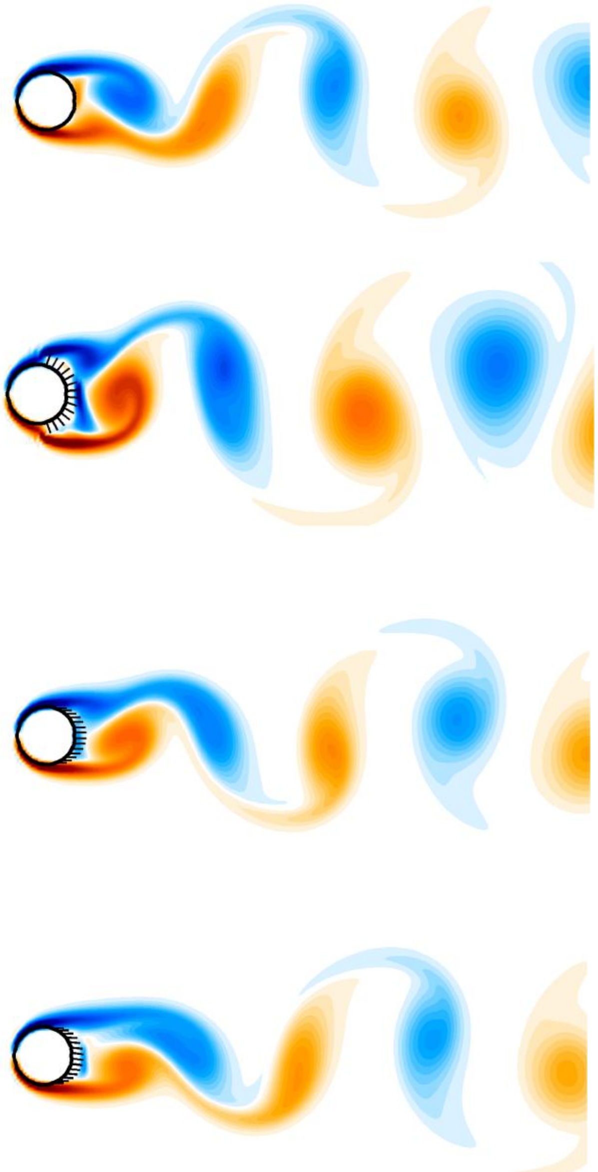
The initial configuration



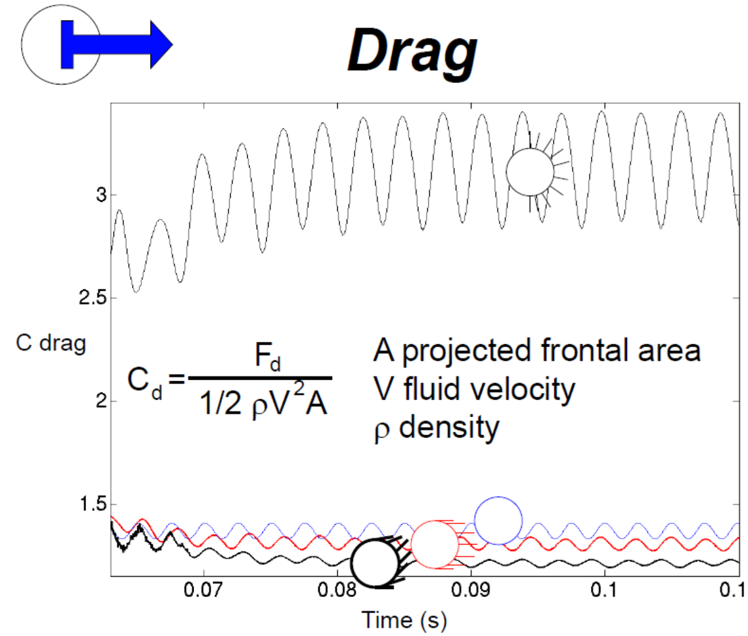
Circular cylinder, Re=200

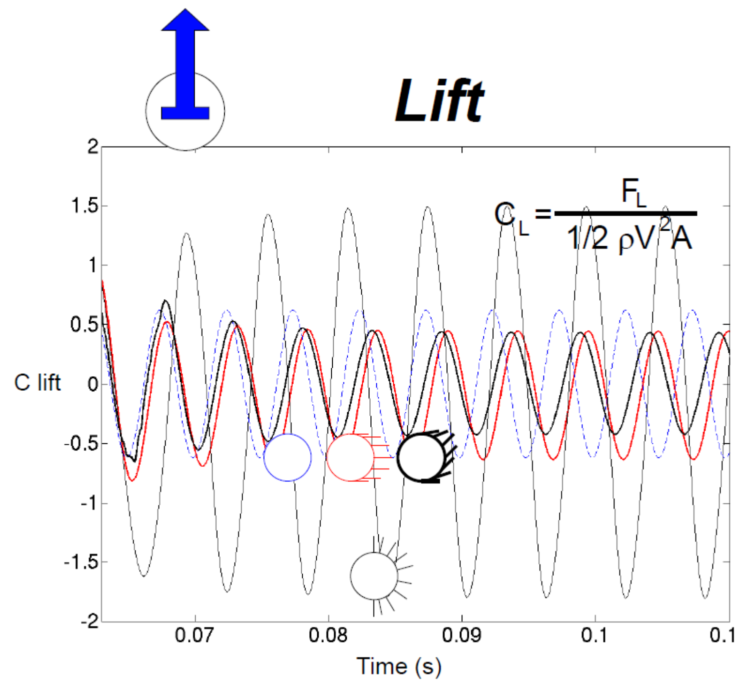
Model of the layer?

Porous, anisotropic and compliant

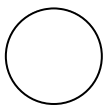
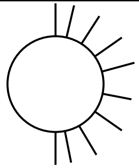
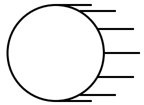
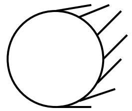


$$T_{fluid} \approx 4\ T_{structure}$$



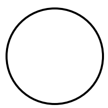
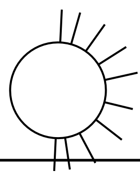
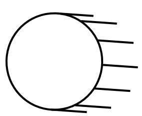
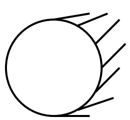


Aerodynamic performances

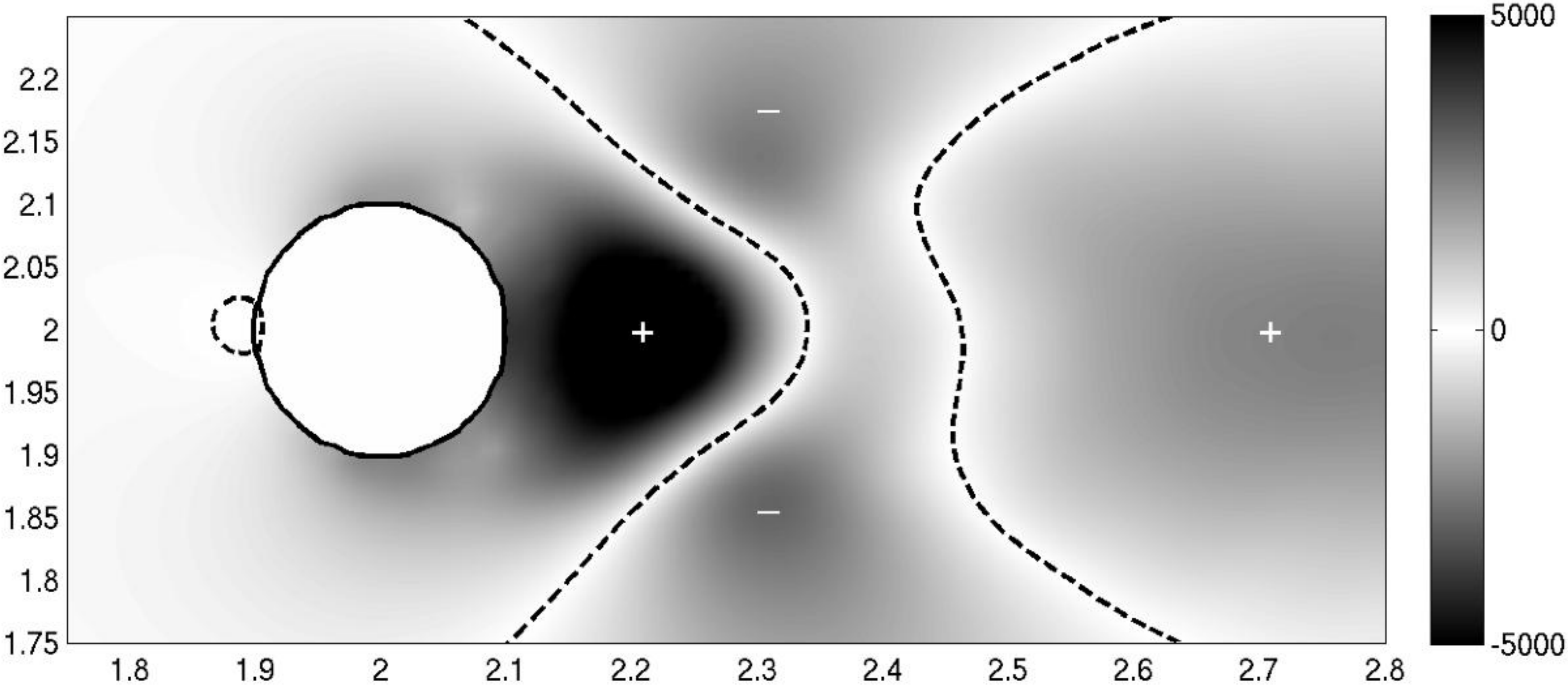
	$<C_d>$	C_d'	C_l'	St
Case 1 	1.3689 (1.39;1.356)	0.0274	0.4381	0.199 (0.199;0.198)
Case 2 	3.1464	0.1943	1.1376	0.1946
Case 3 	1.3035	0.0207	0.3839	0.1916
Case 4 	1.2109	0.012	0.3008	0.1661

(Bergmann *et al.*, *PoF* 2005 ; He *et al.*, *JFM* 2000)

Aerodynamic performances

	$\langle C_d \rangle$	C_d'	C_l'	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%

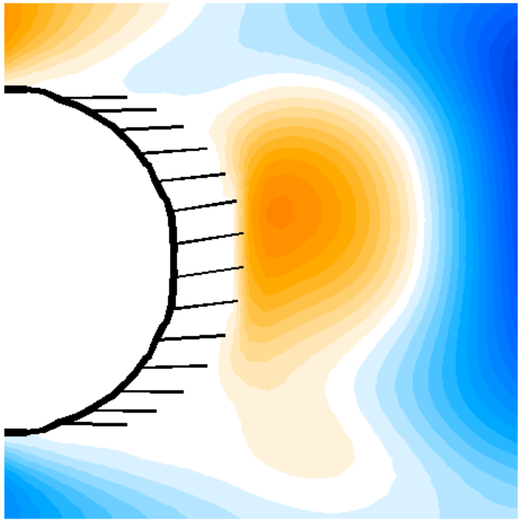
Physical mechanism



Difference of time-averaged pressure field

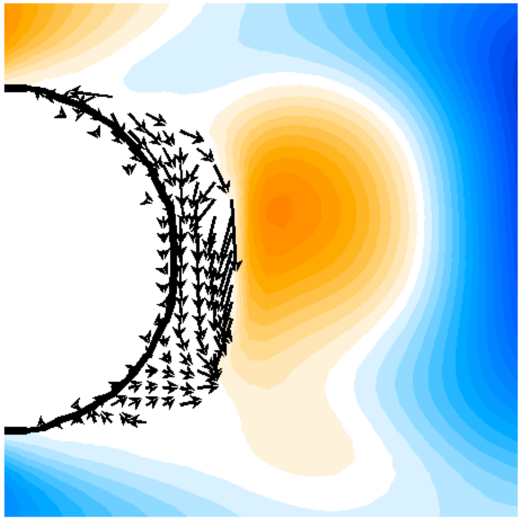
<P with hair>-<P ref>

Physical mechanism



Contours of vertical velocity

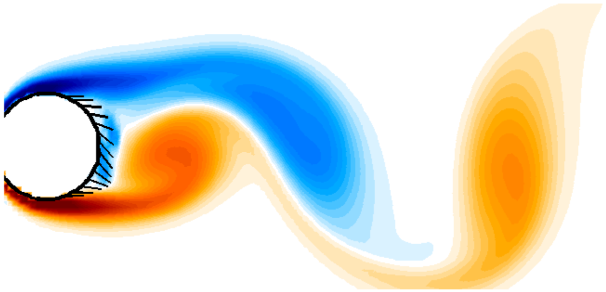
Movements of *reference* cilia



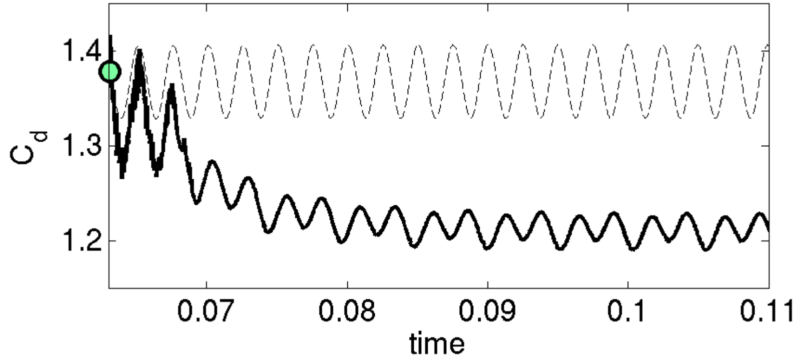
Contours of vertical velocity

Force field

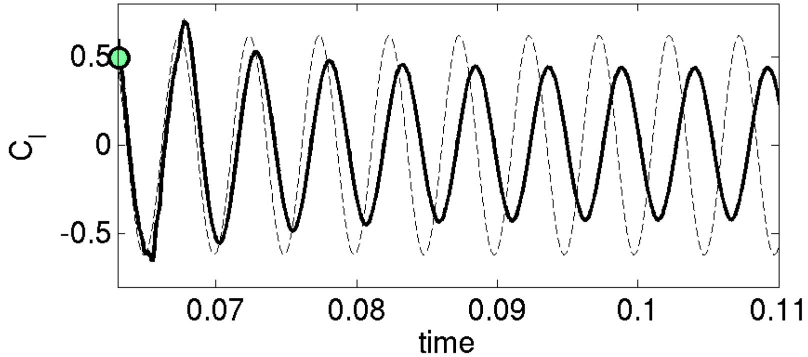
The hairy layer counteracts flow separation



Optimal self-adaptive hairy layer



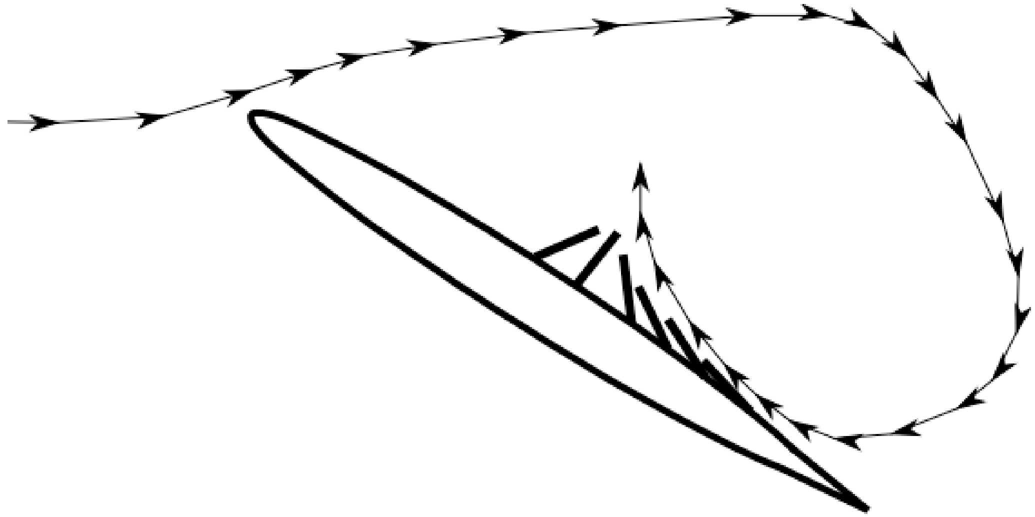
15% drag reduction



40% reduction in lift fluctuations

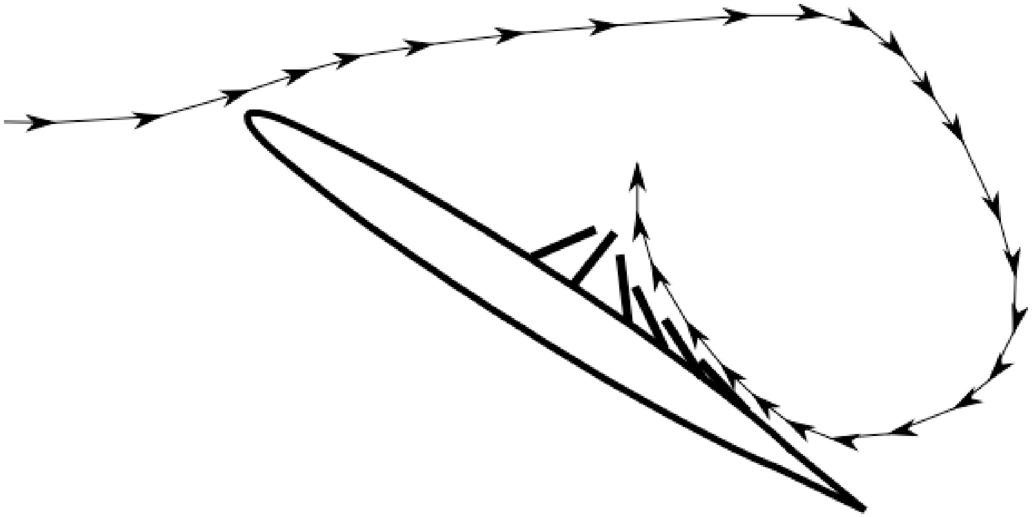
Favier, Dauptain, Basso & Bottaro, *JFM* 2009

airfoil



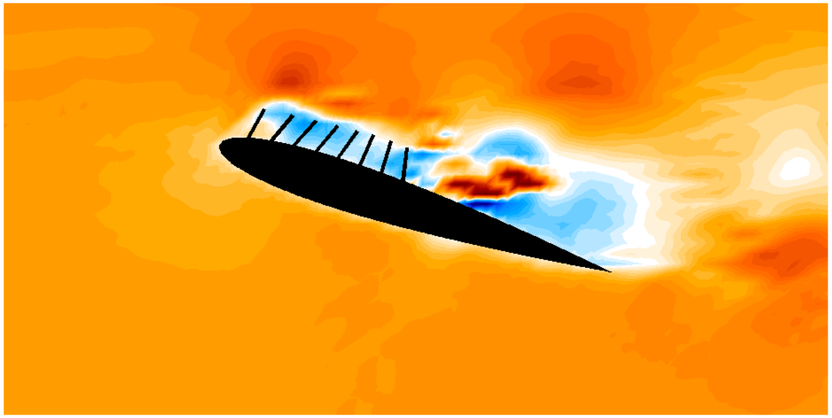
Consider a airfoil: the control elements (the "feathers") must be placed in the position of largest *sensitivity* to achieve an effect

Hairfoil



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

Hairfoil (simulations)

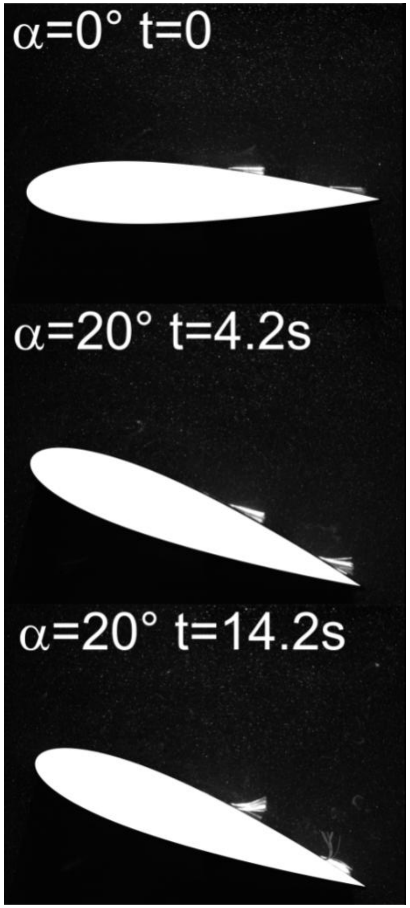


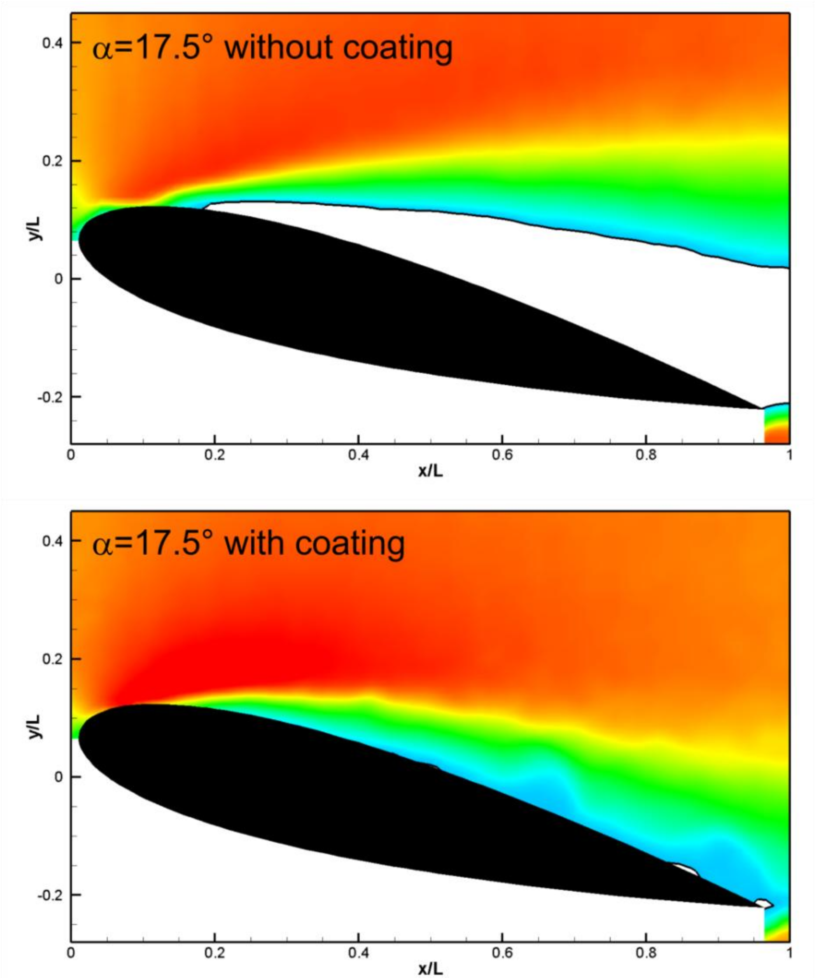
Potential applications:

MAV/UAV
Wind turbines
Hydraulic machines (cavitation?)
Sound mitigation
…

Venkataraman & Bottaro, *PoF* 2012

Hairfoil (experiments)





Kunze & Brücker, *CRAS* 2012

… but this is another story!

THANK YOU!