Hydrodynamics of beating cilia

A. Dauptain, J. Favier, A. Bottaro

DICAT, University of Genova, Italy

Sponsored by the EU, VI Framework Programme, through the FLUBIO Project

IUTAM Symposium on Separated Flows and their Control - June 18-22, 2007, Corfu, Greece

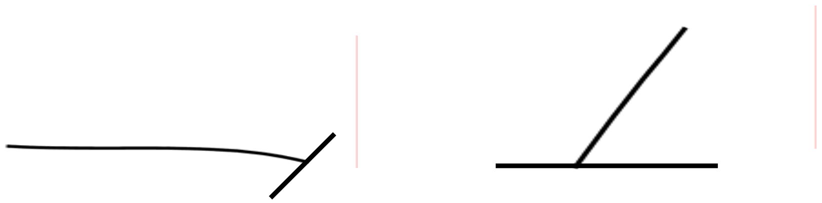
Overview

1. *“The importance of being cilia”*
2. Numerical procedure
3. Results
4. Towards separation control
5. Conclusions and perspectives

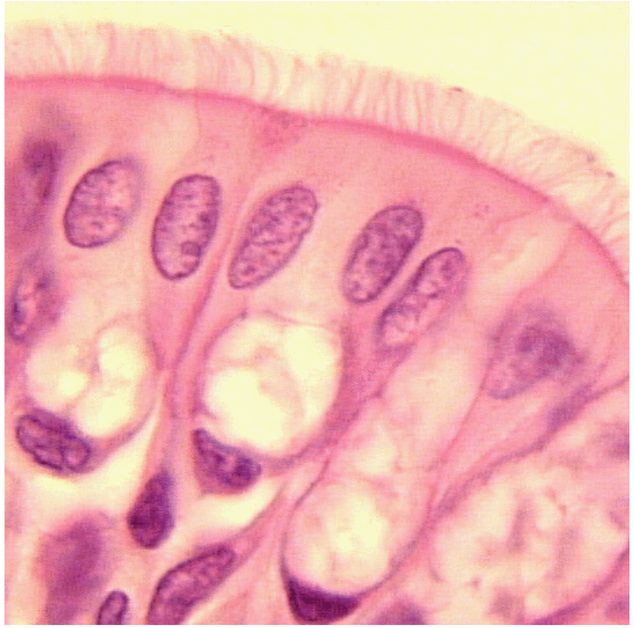
Beating cilia

Human body

Numerous functions played by cilia and flagella in ***human body:***



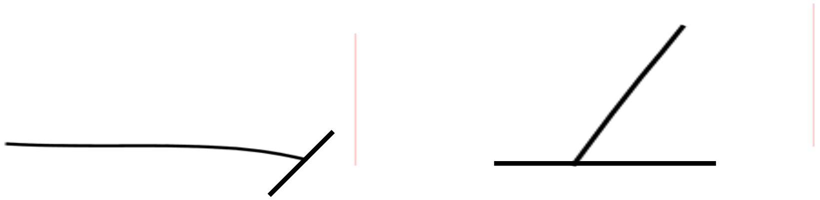
- **Ciliated walls** in many human organs:
  - Fallopian tubes
  - epithelial cells in the trachea
  - cochlea and inner ear, …
- A single flagellum is used by sperm cells to move.
- A better understanding of ciliary defects can lead to treatment of several human diseases.



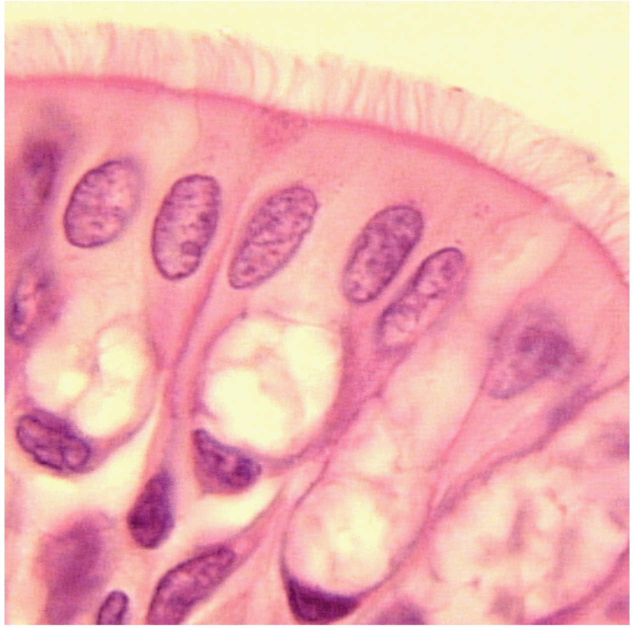
Beating cilia

Human body

Numerous functions played by cilia and flagella in ***human body:***



- **Ciliated walls** in many human organs:
    - Fallopian tubes
    - epithelial cells in the trachea
    - cochlea and inner ear, …
- A single flagellum is used by sperm cells to move.
- Possible use of ciliated actuators for micro-mixers, for flow control in tiny biosensors, as micropumps for drug delivery systems, etc.

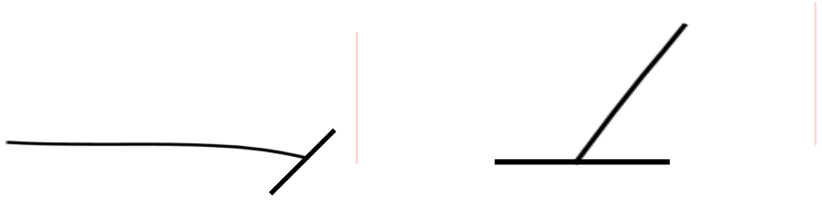


Beating organelles

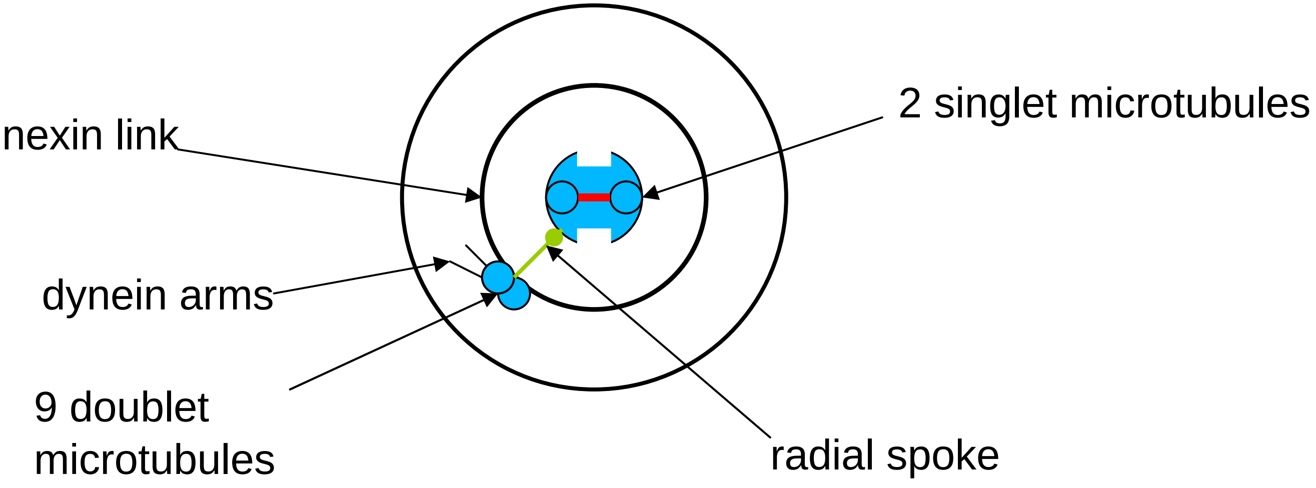
Internal structure

Cilia and eukaryotic flagella

ATP is the biochemical energy source → mechanical work



“9 + 2 axoneme”

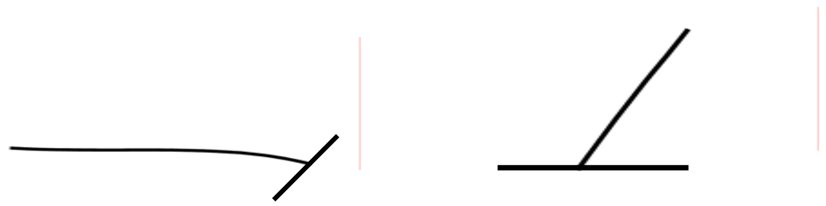


Waveforms are produced by sliding filaments and local curvature control (numerical modelling efforts reviewed by Fauci and Dillon, *ARFM* 2006)

Beating cilia

Reynolds number based on propulsive velocity and the organism's typical dimensions ranges from 10^{-6} (many bacteria) to 10^{-2} (spermatozoa)

"Oscillatory" Reynolds number (based on frequency of oscillations and length of the organelles) is about 10^{-2}



→ Stokes flow approximation in a *local interaction model*

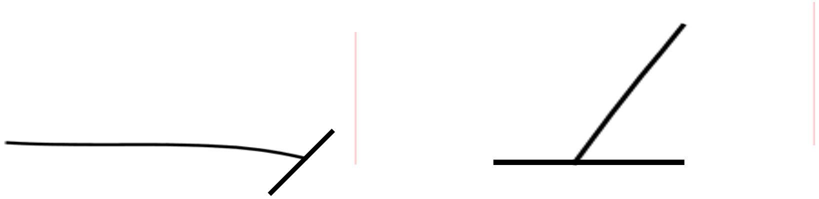
envelope model: cilia are densely packed and form a wavy envelope impermeable to mass, performing *small amplitude* oscillations. Translation arises from the quadratic combination of first-order oscillatory terms (G.I. Taylor 1951; Tuck 1968; Brennen 1974)

Beating cilia

External hydrodynamics

Reynolds number based on propulsive velocity and the organism's typical dimensions ranges from 10^{-6} (many bacteria) to 10^{-2} (spermatozoa)

"Oscillatory" Reynolds number (based on frequency of oscillations and length of the organelles) is about 10^{-2}



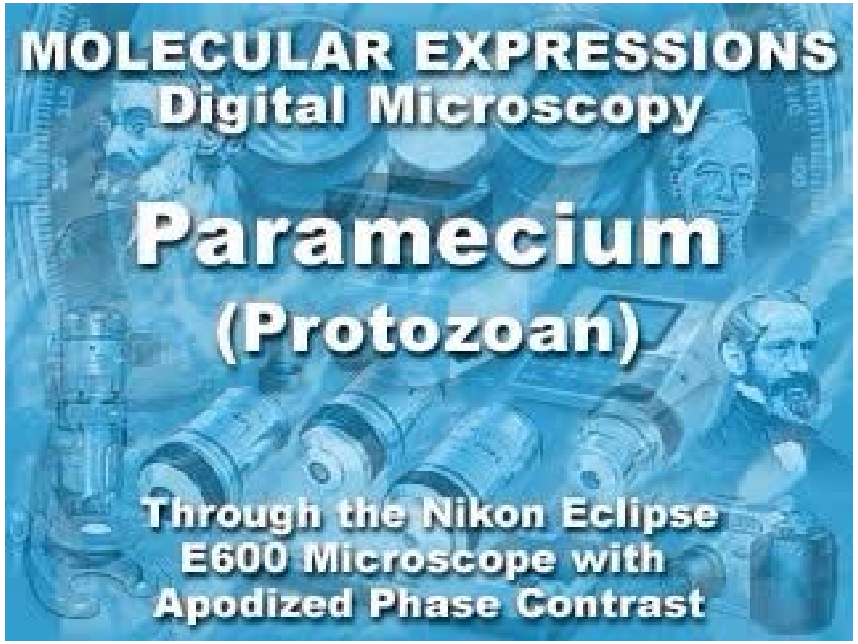
→ Stokes flow approximation in a *local interaction model*

sublayer model: sequence of Stokeslet singularities placed along each organelle, with (known) resistive coefficients in the directions normal and tangential to the organelle; slender body approx. Valid when cilia are sufficiently widely spaced (Blake 1972; Keller, Wu & Brennen 1975, Lighthill 1976)

Beating cilia

Propulsion of small invertebrates

Ciliated propulsion at small Reynolds numbers

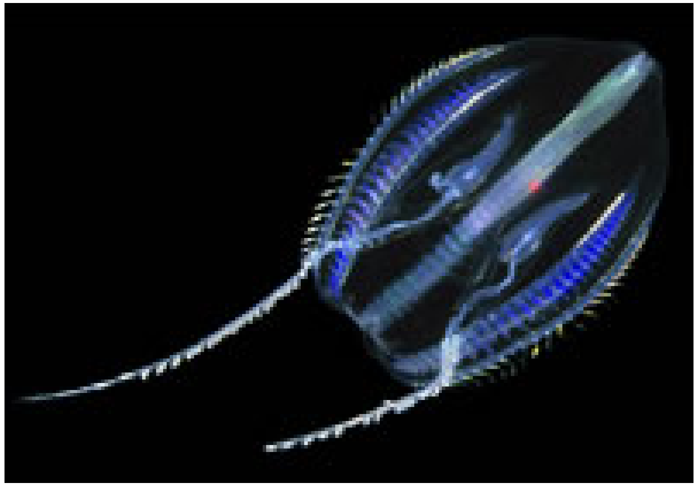


Locomotion of a Paramecium
(body length B $\approx$ *0.15 mm,*
cilia length L $\approx$ *12* μ*m,*
typical beating frequency f $\approx$ *29 Hz,*
dexioplectic and/or antiplectic
metachronism)

$$Re_{oscillatory} = \omega L^2/\nu = 0.026$$

Beating cilia

Ciliated propulsion at not-so-small Reynolds numbers



(body diameter D $\approx$ 1 cm,
cilia length L $\approx$ 1 mm,
typical beating frequency f $\approx$ 20 Hz)

$\mathrm{Re}_{\mathrm{oscillatory}} \approx 125$

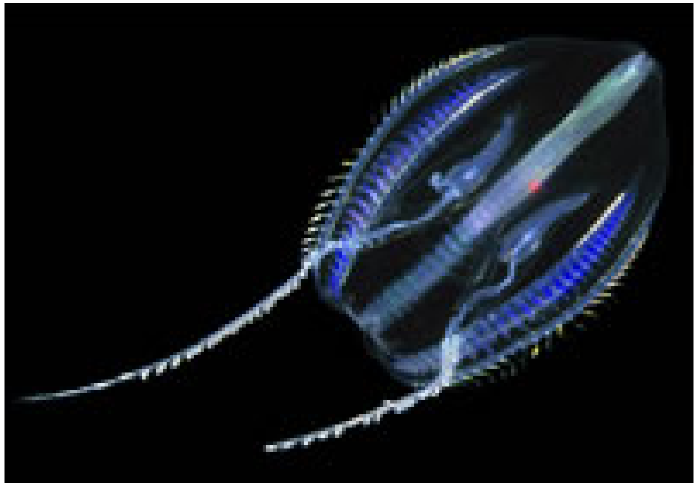
Pleurobrachia Pileus (known as sea-gooseberry or comb-jelly)

Kingdom	*Animalia*
Phylum	*Ctenophora*
Class	*Tentaculata*
Order	*Cydippida*
Family	*Pleurobrachiidae*

Beating cilia

Propulsion of small invertebrates

Ciliated propulsion at not-so-small Reynolds numbers



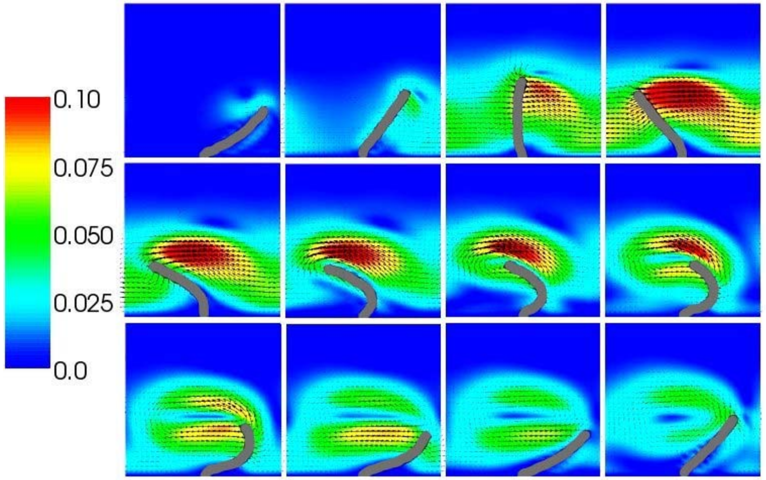
(body diameter $D \approx 1$ cm,
cilia length $L \approx 1$ mm,
typical beating frequency $f \approx 20$ Hz)

$\mathrm{Re}_{\mathrm{oscillatory}} \approx 125$

Pleurobrachia Pileus (known as sea-gooseberry or comb-jelly)

Kingdom	*Animalia*
Phylum	*Ctenophora*
Class	*Tentaculata*
Order	*Cydippida*
Family	*Pleurobrachiidae*

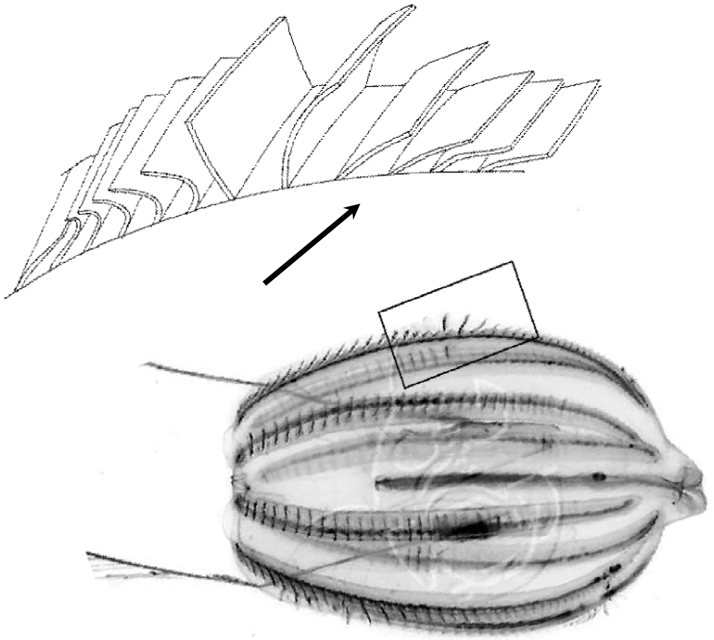
Motion of a single cilium starting from rest



Beating cilia

Propulsion mechanisms of Pleurobrachia

“Planar” beat patterns of combplates generate surface waves:

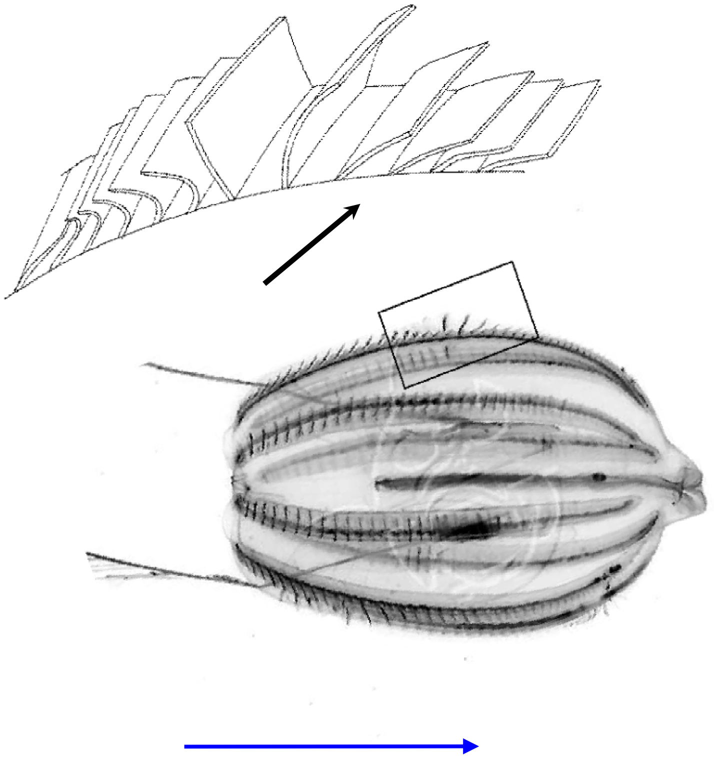


Propulsion

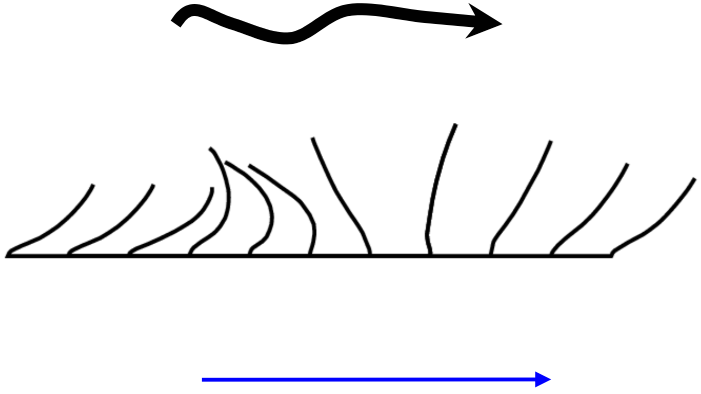
Beating cilia

Propulsion mechanisms of Pleurobrachia

“Planar” beat patterns of combplates generate surface waves:



Propulsion



Antiplectic metachronal wave

Propulsion of the organism

Outline

1. Importance of beating cilia
2. Numerical procedure
3. Results
4. Towards separation control
5. Conclusions and perspectives

Numerical procedure

General overview

The problem is decomposed into three subproblems:

CILIA MOTION

Movement of the structure

NTMIX

Fluid solver

PALM

Coupler

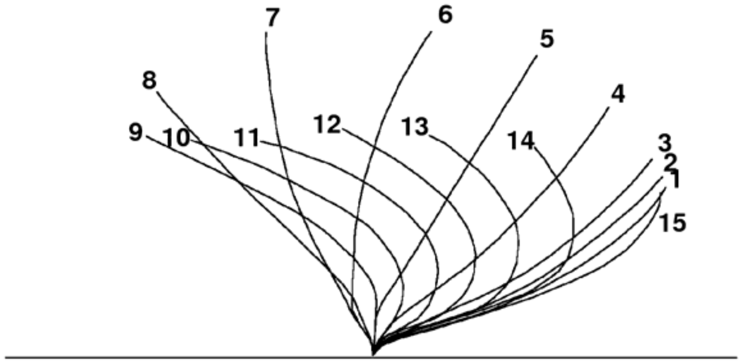
Numerical procedure

General overview

Extraction of position and velocity of each cilium

CILIA MOTION

Movement of the structure



NTMIX

Fluid solver

PALM

Coupler

Numerical procedure

General overview

DNS of incompressible flow

CILIA MOTION

Movement of the structure

NTMIX

Fluid solver

8th order in space

3rd order in time

32 x 32 orthoregular grid *per cilium*

CFL number is fixed to 0.3

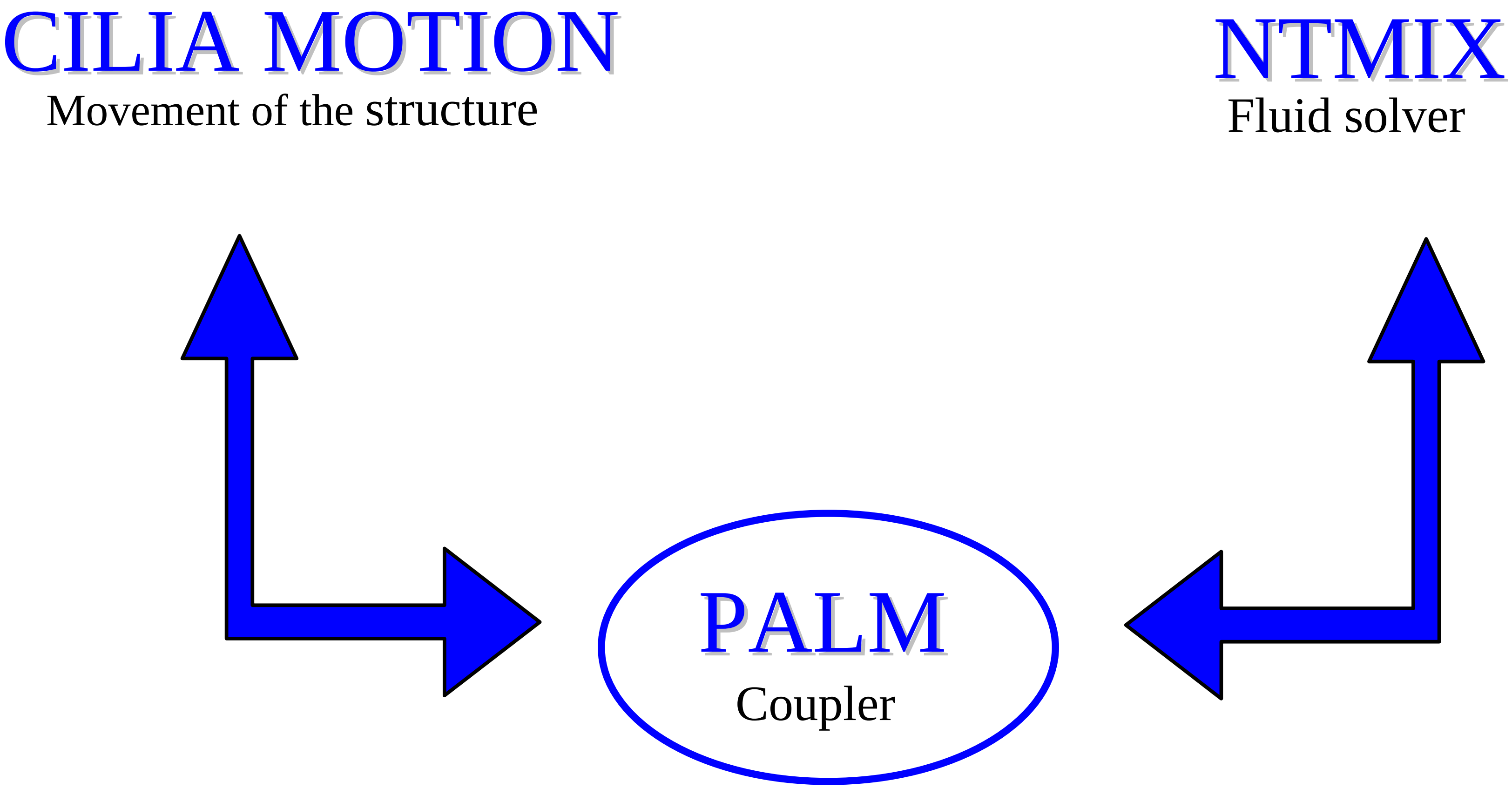
PALM

Coupler

Numerical procedure

General overview

Coupling is performed by PALM



CILIA MOTION
Movement of the structure

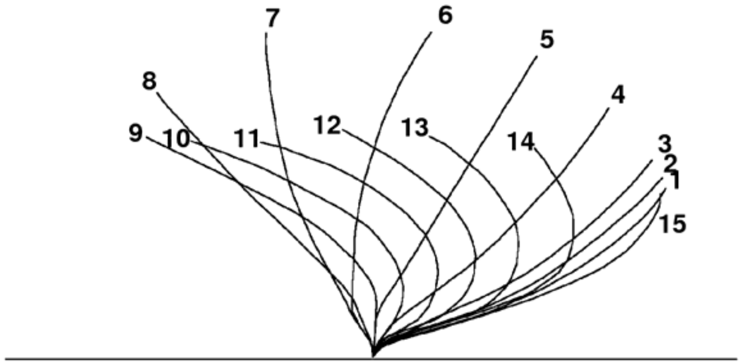
NTMIX
Fluid solver

PALM
Coupler

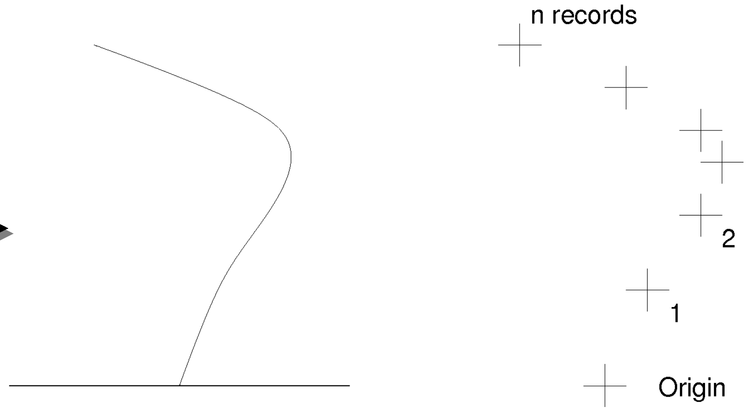
Imposition of ***immersed boundary conditions (IBM)***

Numerical procedure

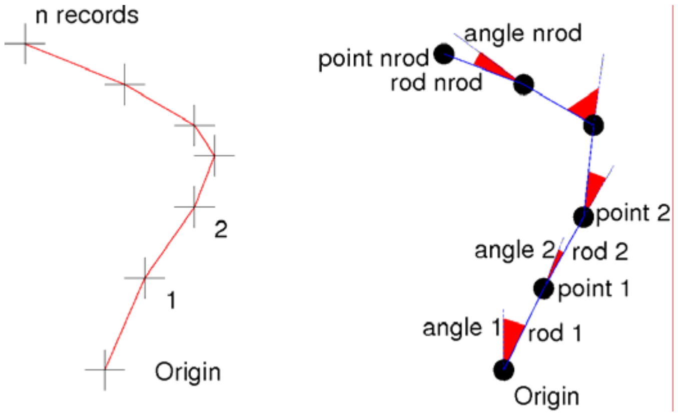
Extraction of position and velocity of each cilium



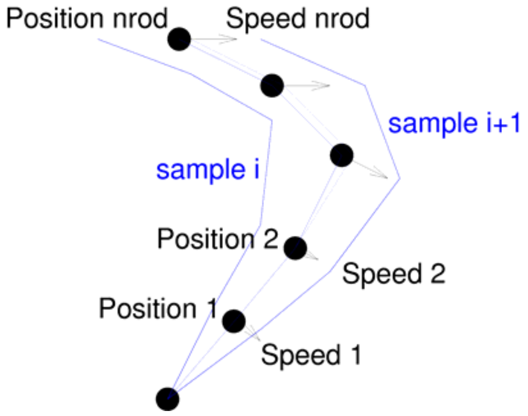
Experiments of Barlow, Sleight & White, J. Exp.Biol, 1993



Motion capture in a xy dataset



Sampling into an angular dataset



Interpolation between samples

Numerical procedure

Immersed Boundary Method

- A volume force field is introduced to model the presence of cilia:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}$$

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

Two IBM strategies are tested and compared on two test cases:

- *Feedback forcing:*

$$\mathbf{f}(\mathbf{x}_s, t) = \alpha_f \int_0^t \left[\mathbf{u}(\mathbf{x}_s, t) - \mathbf{V}(\mathbf{x}_s, t)\right] dt' + \beta_f \left[\mathbf{u}(\mathbf{x}_s, t) - \mathbf{V}(\mathbf{x}_s, t)\right]$$

- *Direct forcing*:

$$\mathbf{f}^{l+1}(\mathbf{x}, t) = \frac{\mathbf{V}^{l+1} - \mathbf{u}^{l}}{\Delta t} - \mathbf{RHS}^{l}$$

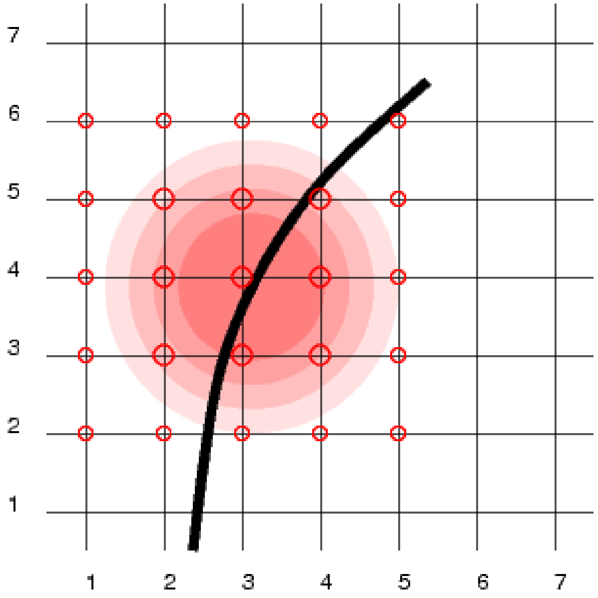
Numerical procedure

Immersed Boundary Method

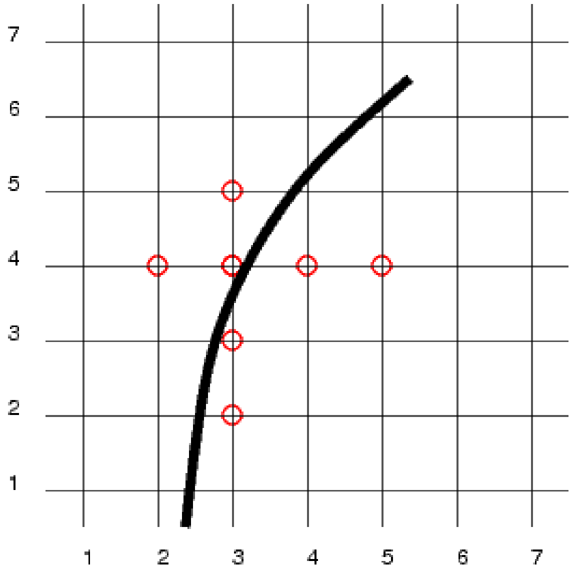
- The DNS is performed on a cartesian mesh. The cilia do not exactly coincide with the nodes → we need to interpolate.

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

- *Distributed interpolation:*



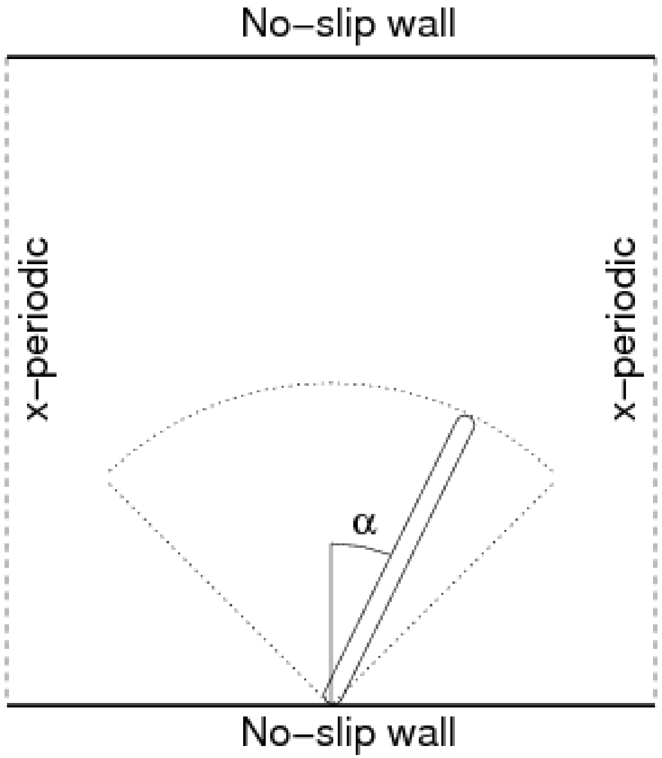
- *Linear interpolation*:

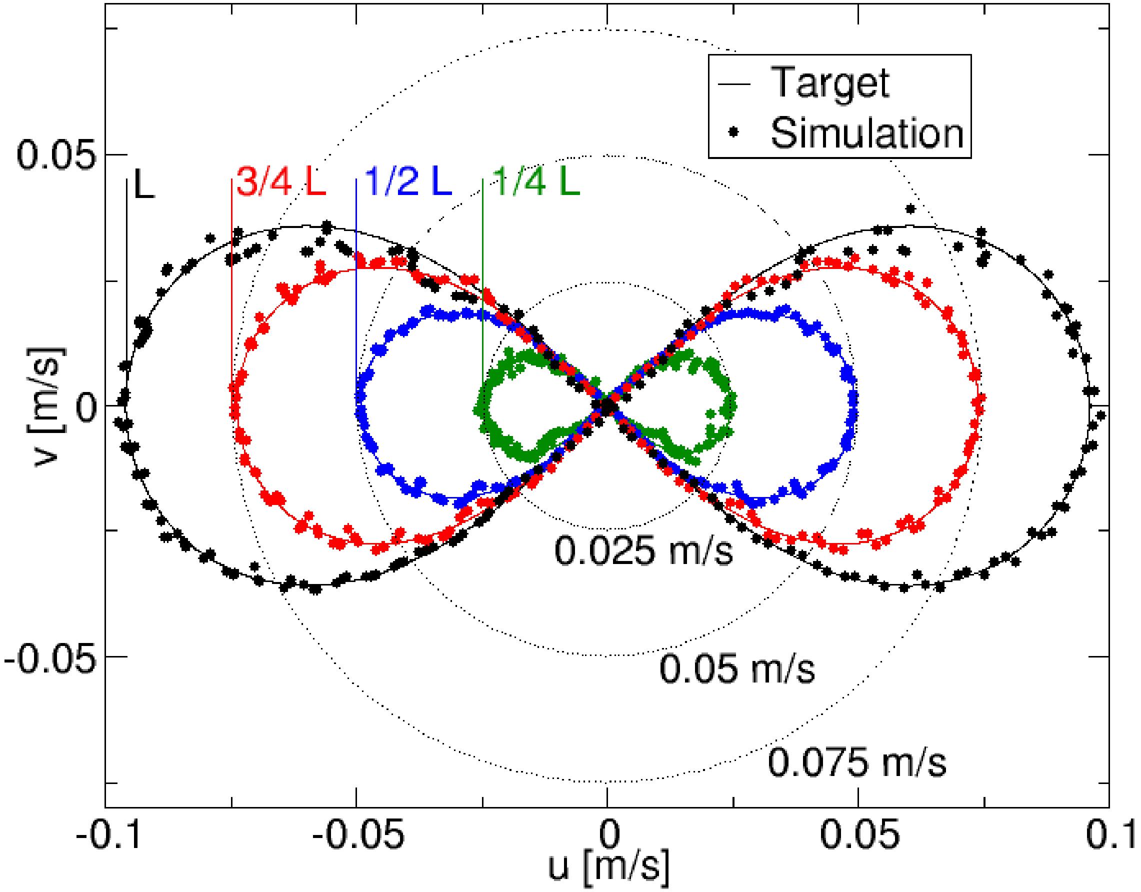


Numerical procedure

Immersed Boundary Method

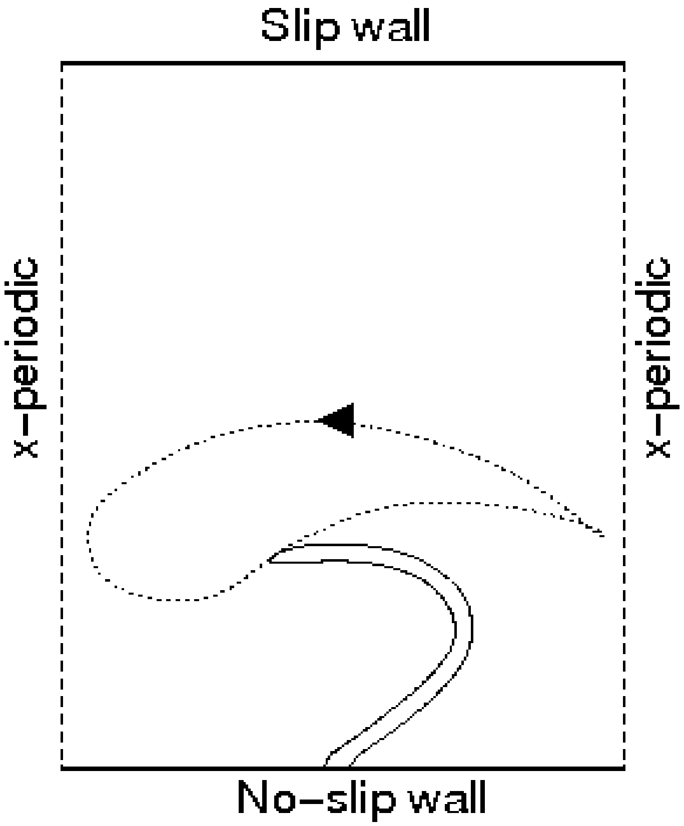
Beating rigid plate test case

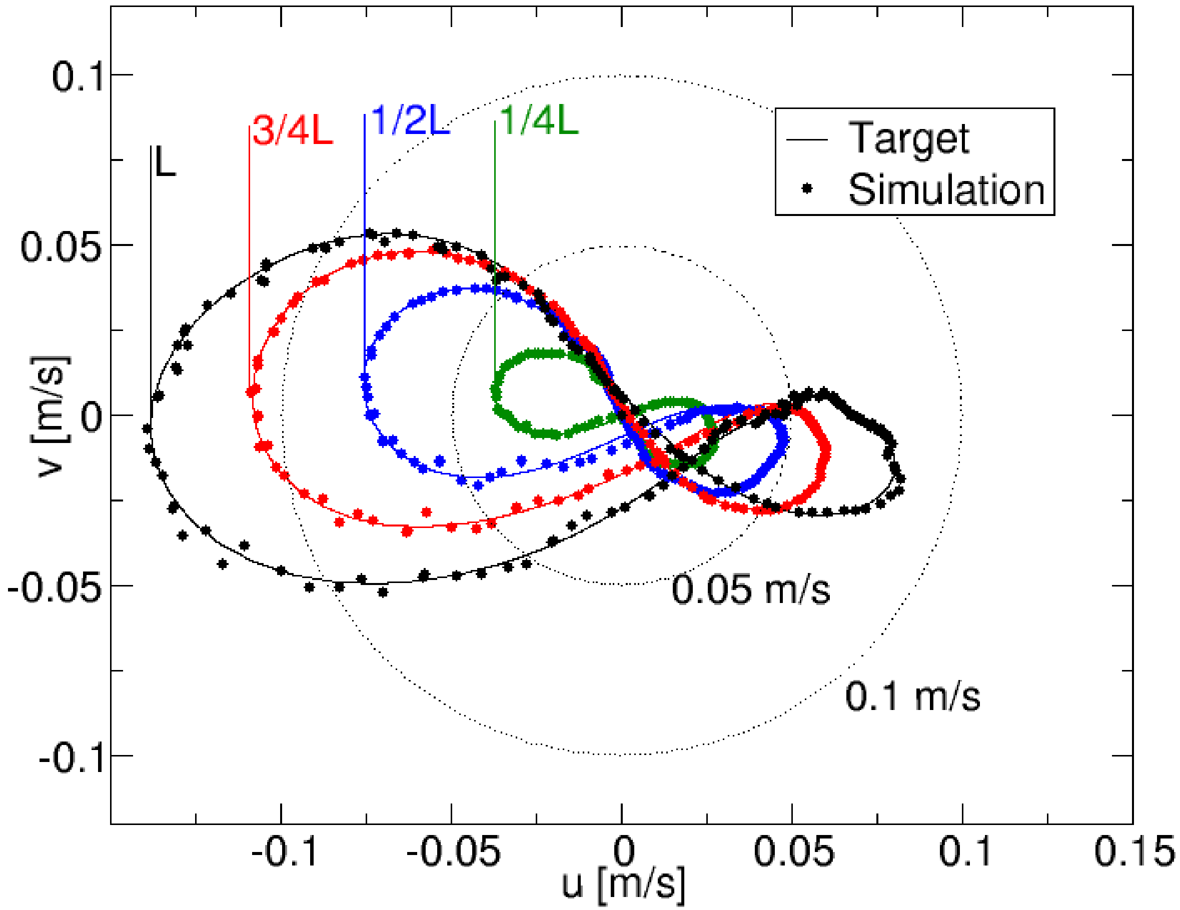




Numerical procedure

Beating flexible cilium test case





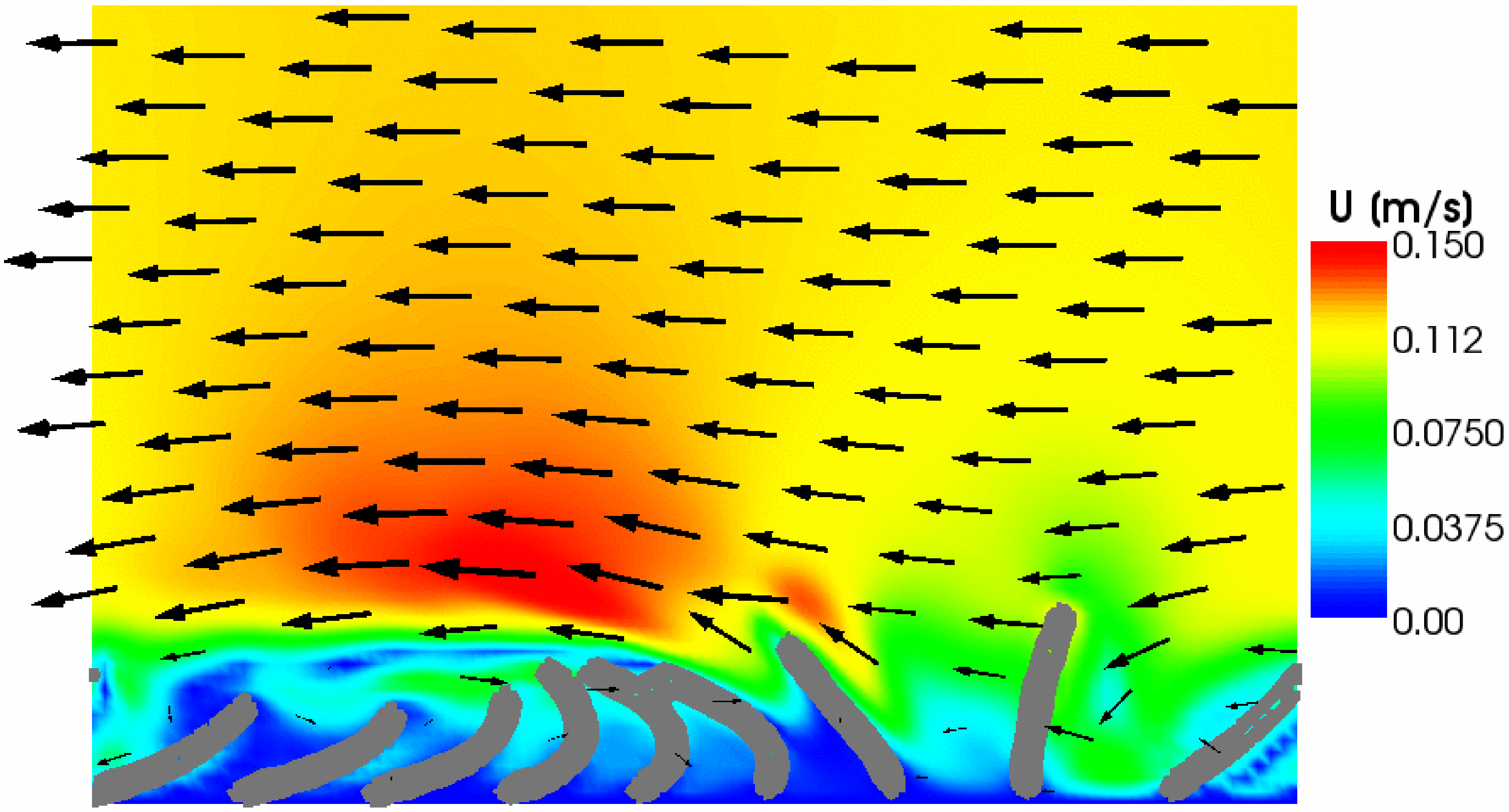
Outline

1. Importance of beating cilia
2. Numerical procedure
3. Results
4. Towards separation control
5. Conclusions and perspectives

Results

Velocity fields

9 combplates beating at 15Hz

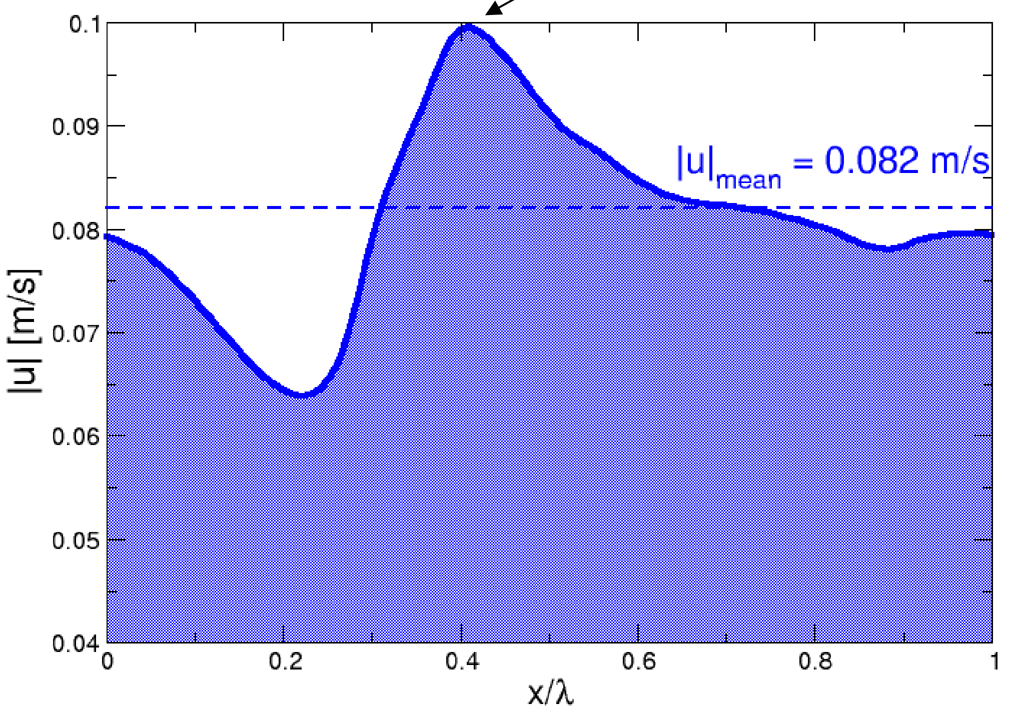


Velocity vectors (arrows) together with velocity modulus (colours)

Results

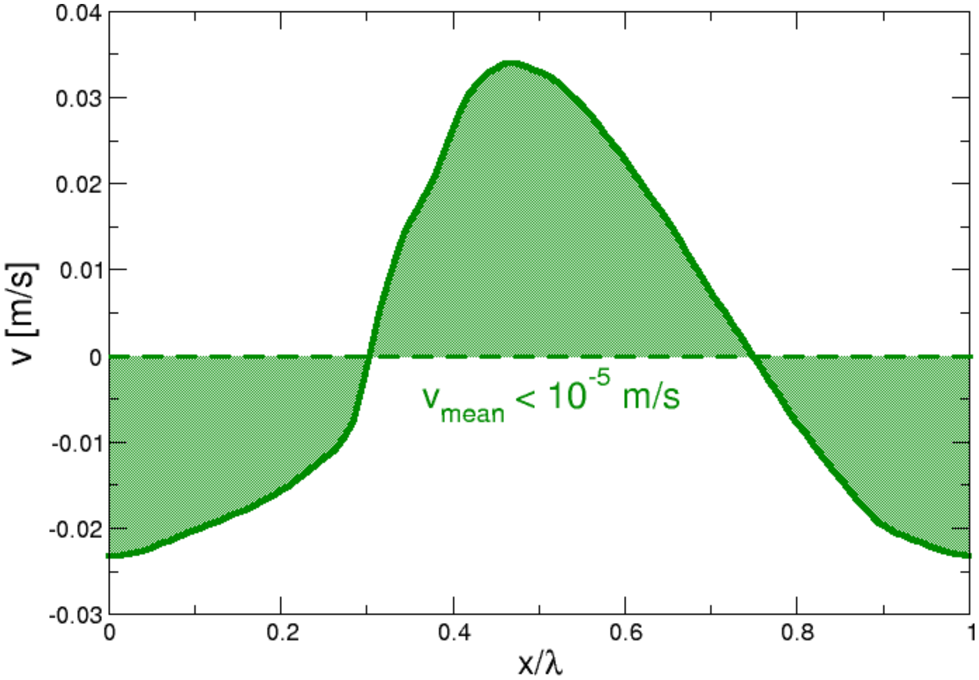
Velocity profiles

end of the effective stroke phase



Modulus of the longitudinal velocity at y = 0.9 L

blowing/suction effect



Vertical velocity

Results (varying wavelengths λ)

Parametric study

Wave phase speed $c = f \lambda = f N L / 2$ varies from 0.061 m/s to 0.113 m/s

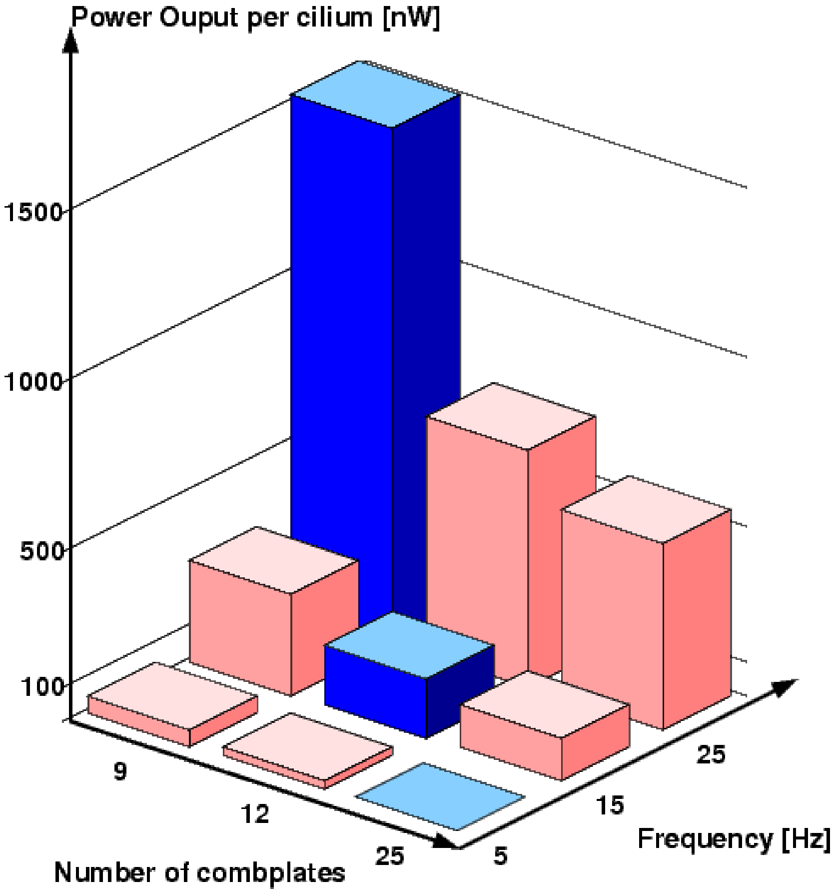
Power output (nW/cilium)	N = 9 λ=4.5 mm	N = 12 λ=6 mm	N = 25 λ=12.5 mm	U/U_{cilium}	N = 9	N = 12	N = 25	Max $[U_{cilium}]$ *(ωL)*	$\frac{U}{\text{Power p.c.}}$
f = 5 Hz	12.7	8.2	6.3		1.08	1.02	0.83	0.035 m/s *(0.0314 m/s)*	4.6×10^{-3}
f = 15 Hz	236	158	113		1.2	1.16	1.03	0.105 m/s *(0.0942 m/s)*	7.7×10^{-4}
f = 25 Hz	1565	697	529		1.56	1.18	1.07	0.175 m/s *(0.157 m/s)*	1.7×10^{-4}

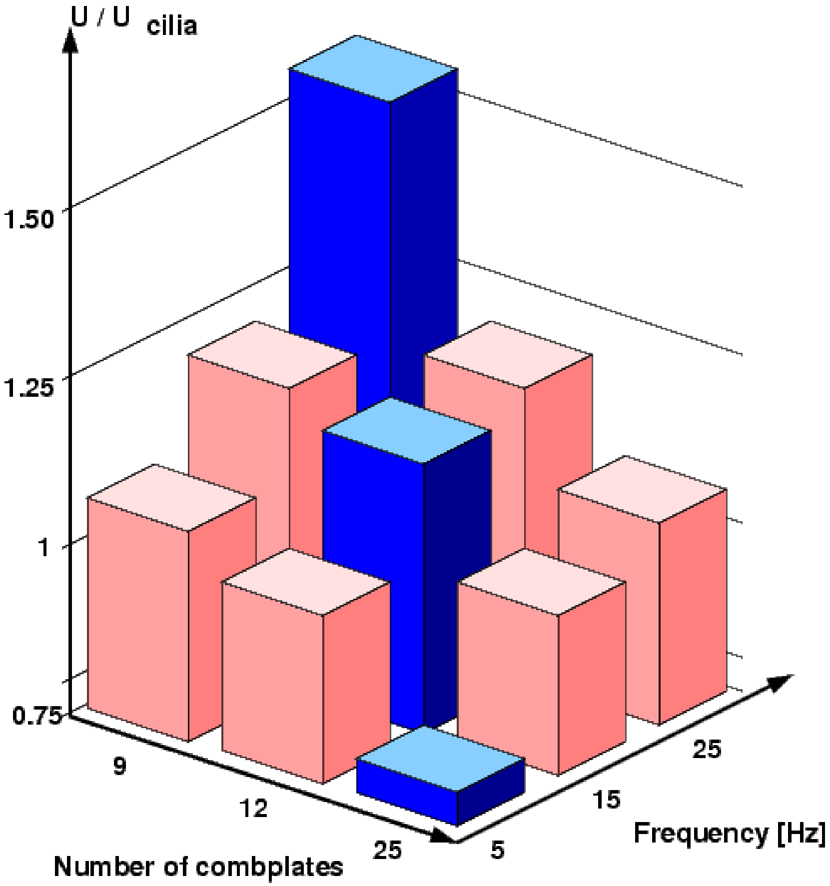
"Natural" spacing between neighboring cilia, i.e. 0.5 L.

The *Pleurobrachia* adapts its motion in function of the currents, presence of predators/preys, etc. Frequency and wavelength chosen are environmental functions.

Results

Parametric study

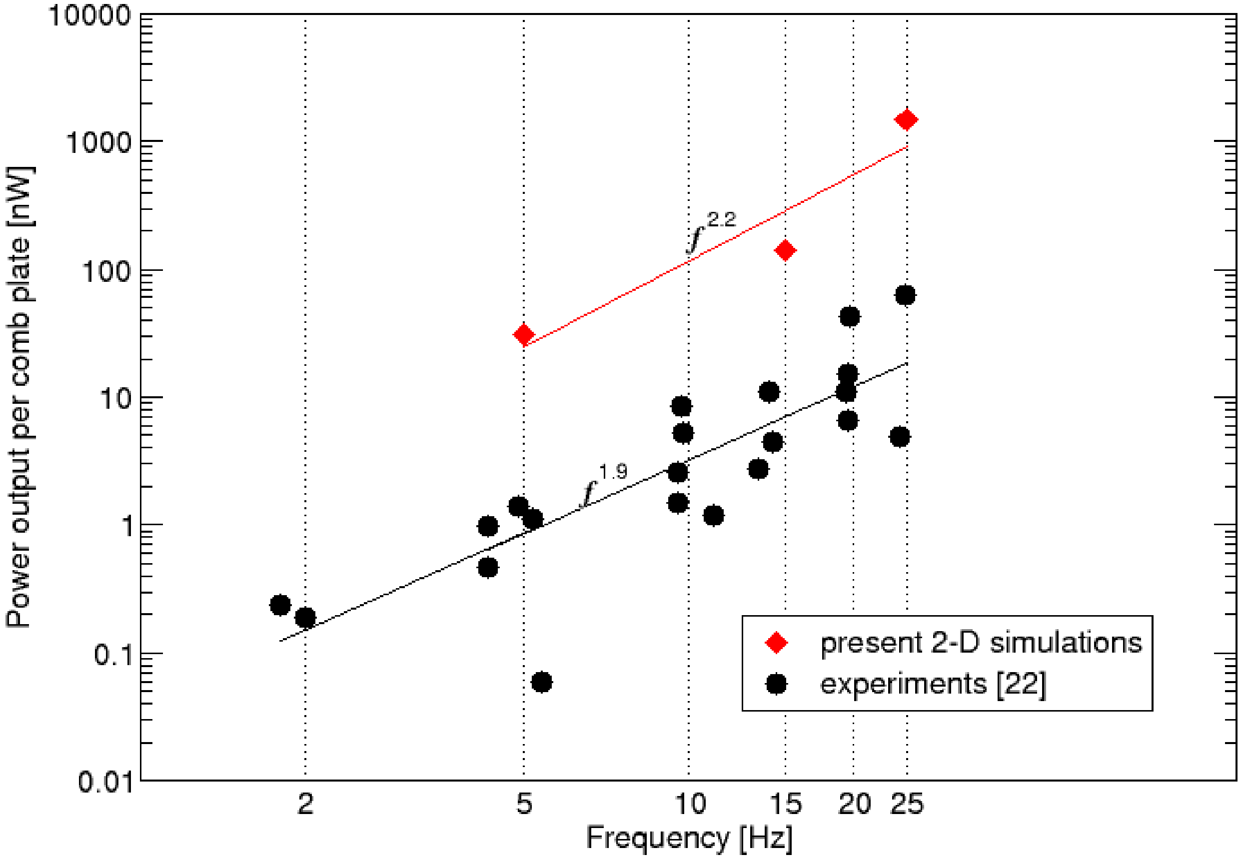




Results

Power output

Power outputs per combplate as function of the beating frequency



→ *Qualitative agreement with experiments*

Results

Power output

$$\begin{cases} P \sim f^{3}\, N^{-1.21} \\ U \sim f^{1.13}\, N^{-0.25} \end{cases}$$

Combining these two relations it can be found that the power expended to displace the Pleurobrachia at constant speed U varies like $N^{0.21}$ or $f^{0.5}$

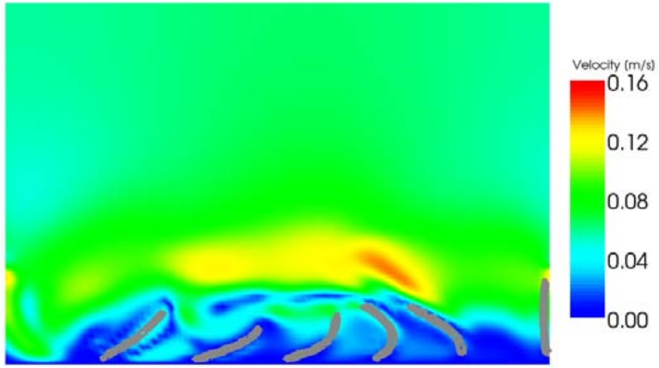
→ relatively mild variation with frequency or number of cilia, for the “natural” spacing between neighboring cilia.

Results

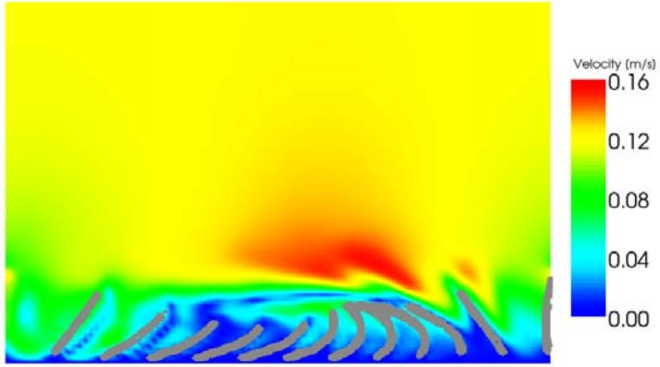
Effect of cilia spacing

“Non-natural” spacing, f = 15 Hz

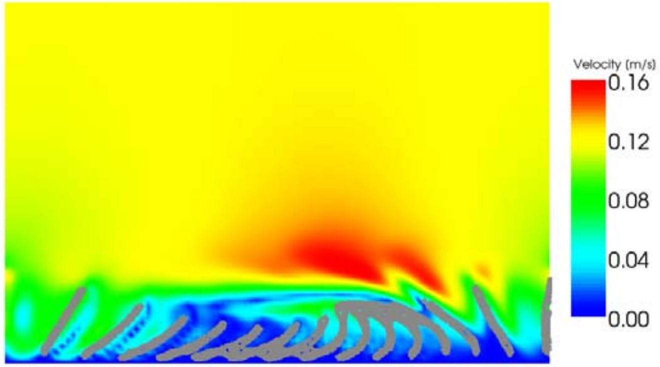
Fixed wavelength = 6 mm



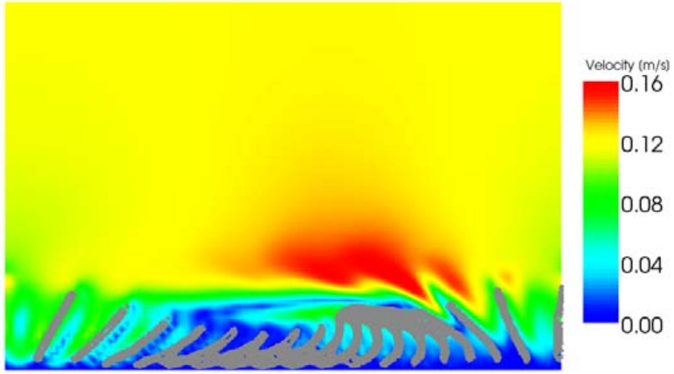
U = 0.1024 m/s, N = 6



U = 0.1218 m/s, N = 12



U = 0.1246 m/s, N = 15

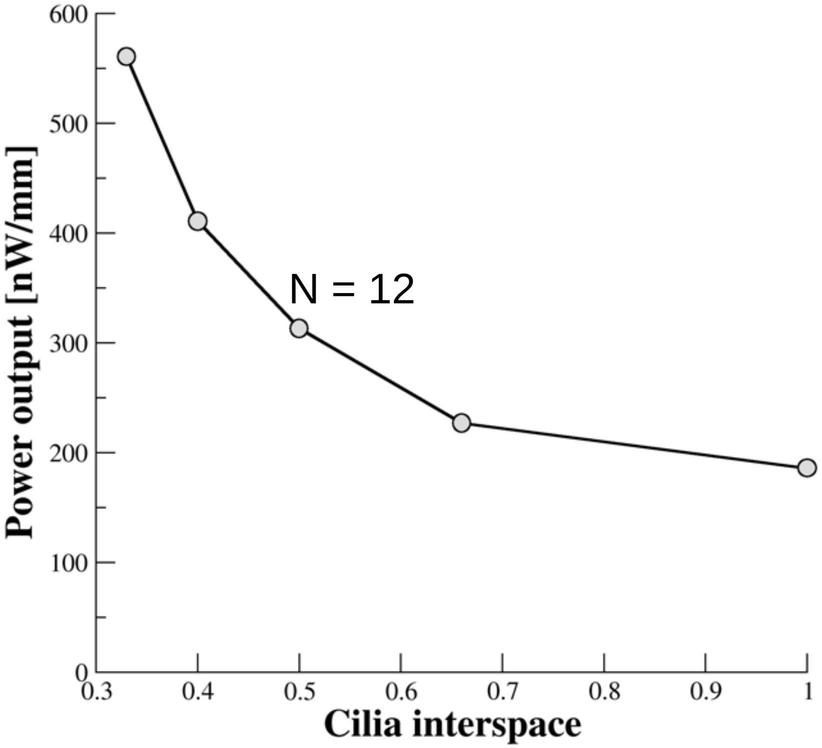


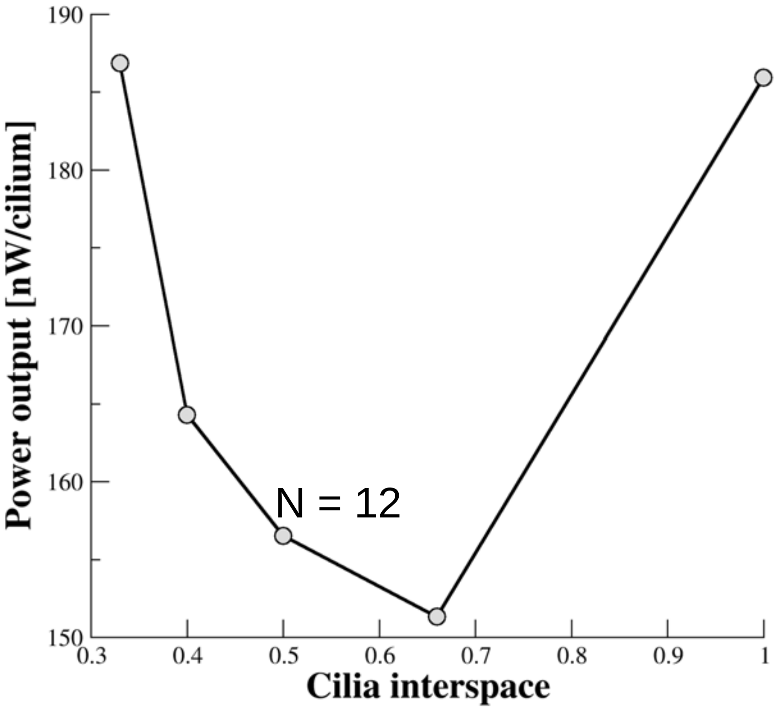
U = 0.1273 m/s, N = 18

Results

Effect of cilia spacing

“Non-natural” spacings


N = 12

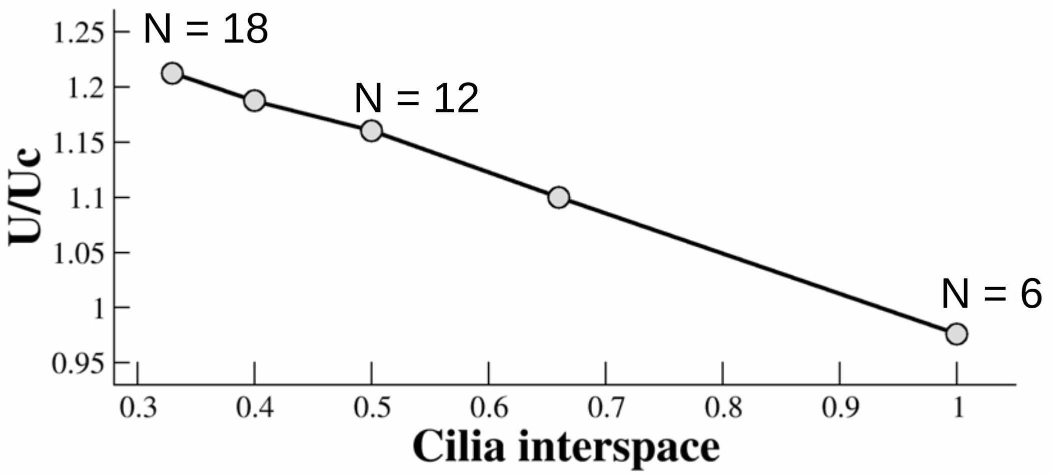

N = 12

Fixed wavelength = 6 mm

Results

Effect of cilia spacing

“Non-natural” spacing



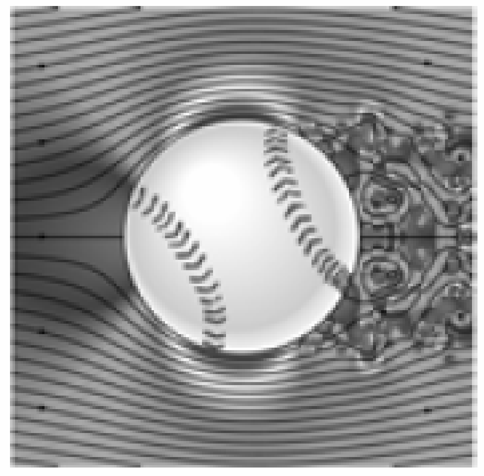
$U/P_{p.c.}$ = 7.7 x 10^{-4} (for N = 12, natural cilia interspace)
$U/P_{p.c.}$ = 7.6 x 10^{-4} (for N = 9)
$U/P_{p.c.}$ = 7.6 x 10^{-4} (for N = 15)

Even in 2D the “natural” spacing (0.5 L) appears to be optimal!

Outline

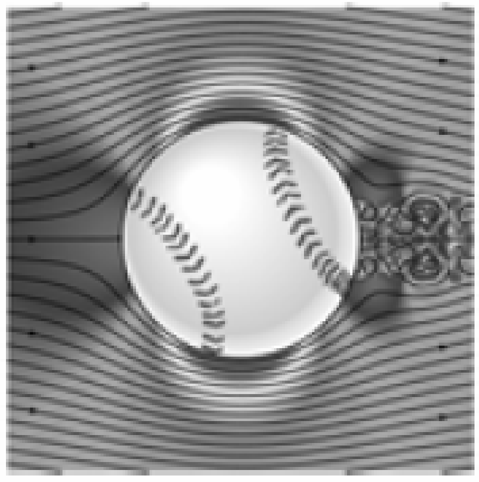
1. Importance of beating cilia
2. Numerical procedure
3. Results
4. Towards separation control
5. Conclusions and perspectives

Control



Big wakes, stall and

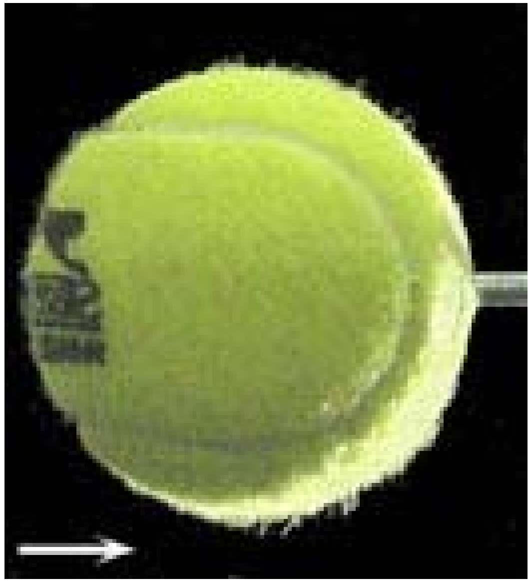
large pressure drag



Fuzz and/or dimples trip the
boundary layer, turbulence
resists separation better,
ex. golf and tennis balls

Control

U = 70 km/h



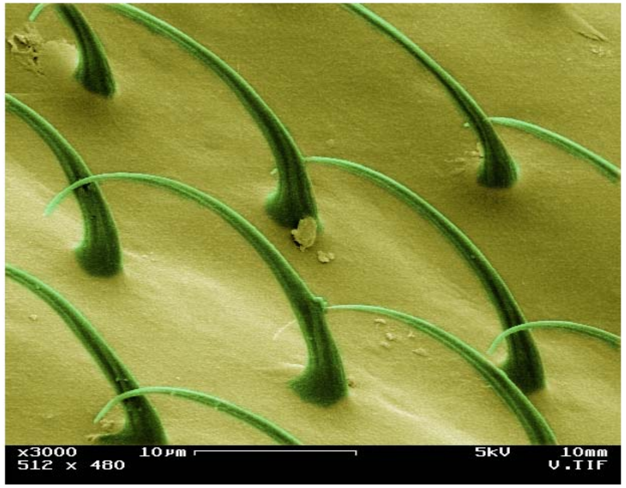
U = 217 km/h

(about the speed of a very fast serve)

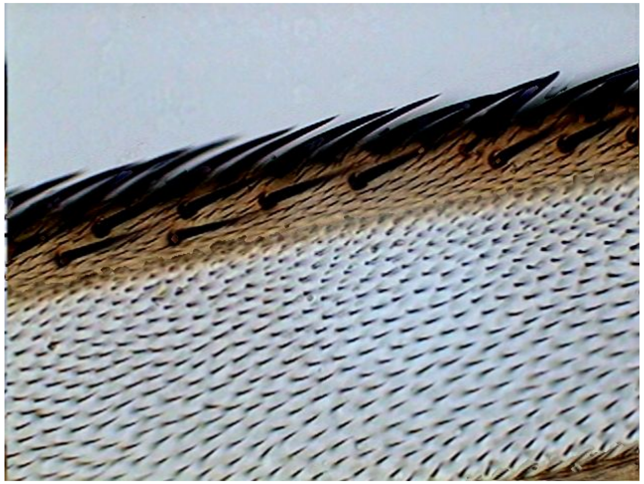
Fuzz is closer to the ball surface, “fuzz drag” created from the airflow over fibers, which interact with all the other fibers around, declines
Mehta R.D. & Pallins J.M., 2001,
The aerodynamics of a tennis ball,
Sports Engineering **4**, 1-13

Control

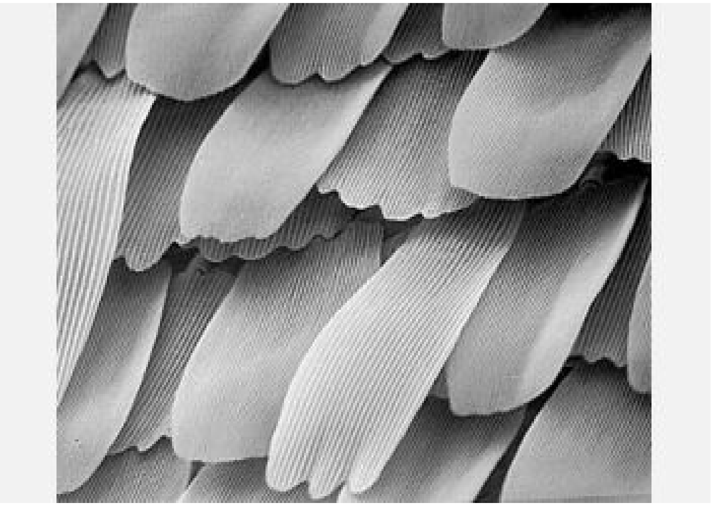
Motivation



Fly



Mosquito



Butterfly

During landing approach or in gusty winds birds have a “biological high lift device”: feathers pop up

Control

Bechert, Bruse, Hage & Meyer, AIAA Paper 97-1960

Movable flaps on wings: artificial bird feathers

2D experiments in a low turbulence wind tunnel at Re = 1-2 x 10^6

- one movable flap attached near the trailing edge of the airfoil and free to pivot → increase of about 10% of max lift
- two arrays of movable flaps, with the upstream one that flutters when activated (to avoid it acting like a spoiler) → during flutter energy is supposedly extracted from the mean flow and fed into the near wall region, effect on the incipient separation bubble and increase of max lift of 6% more

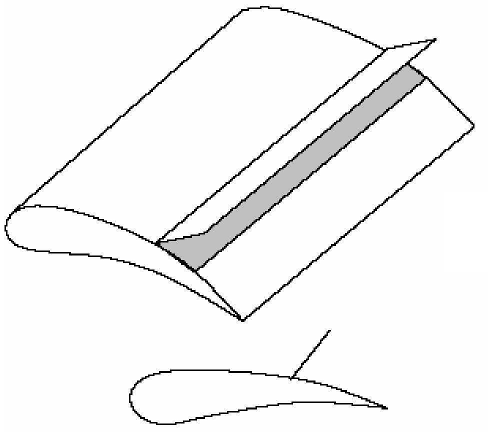
Flight tests on a STEMME S10 motor glider

- increase in lift by about 7% (measured indirectly through the reduction in minimum speed before stall) → test pilot survived!

Control

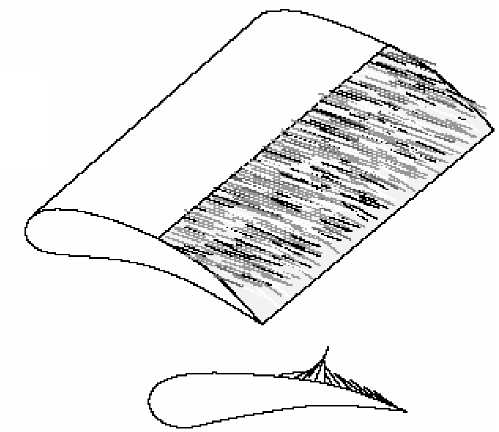
Hairy surfaces

Instead of artificial feathers, hairy surfaces on the suction side of airfoils may be more suited for a number of applications, including MAV, UAV, etc.



Control

Hairy surfaces

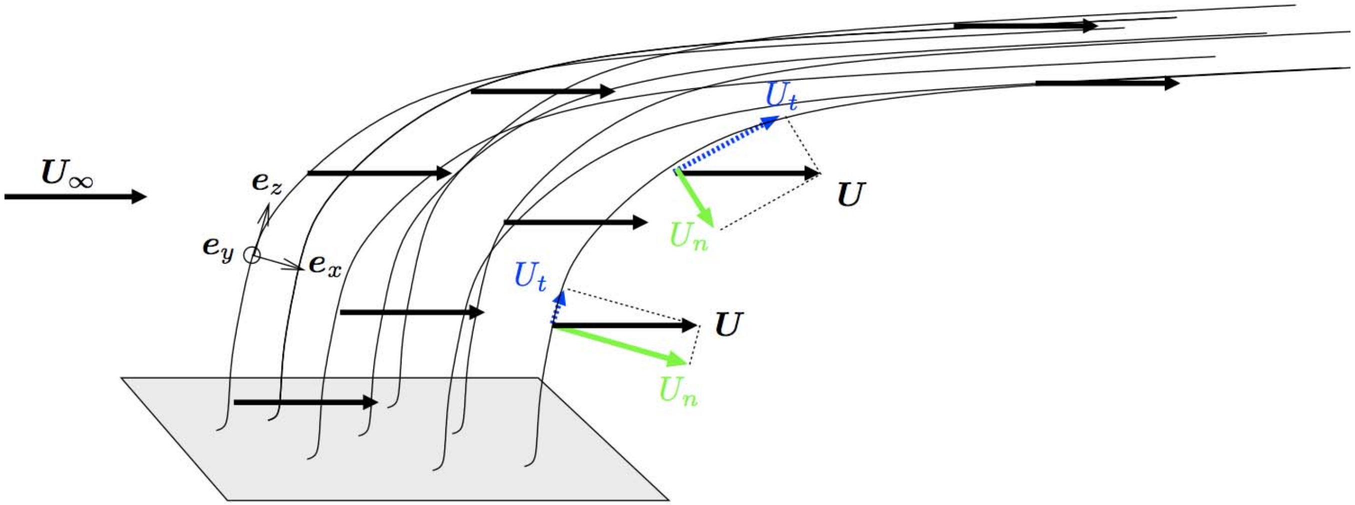


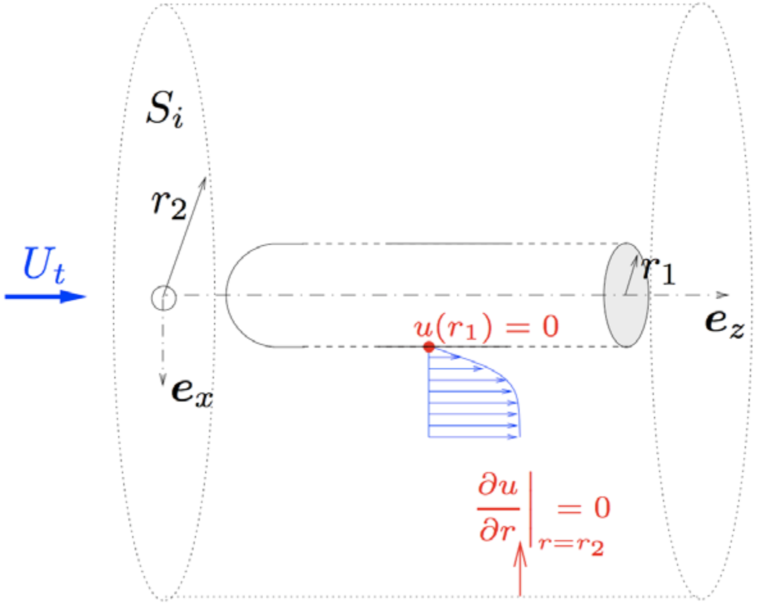
Instead of artificial feathers, hairy surfaces on the suction side of airfoils may be more suited for a number of applications, including MAV, UAV, etc.

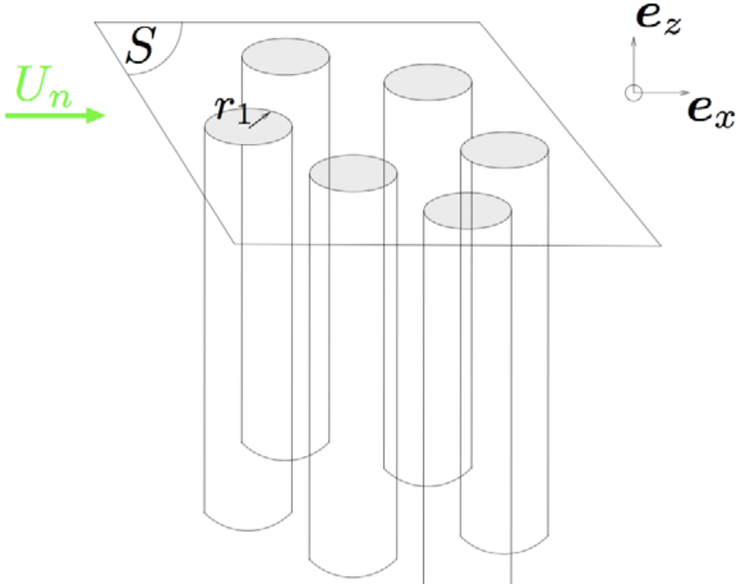
HAIRFOILS !

Control

A model of passive ciliated surfaces







Control

Following the same methodology:

CILIATED WALL

Movement of the structure

NTMIX

Fluid solver

Sea Leopard skin

PALM

Coupler

Control *(what we would like to do in the near future …)*

- Influence of hair (cilia's length, density, modulus of elasticity …) on boundary layer separation.
- Linear stability of some flows using a homogeneized model of passive cilia near the wall.

Outline

1. Importance of beating cilia
2. Numerical procedure
3. Results
4. Towards separation control
5. Conclusions and perspectives

Conclusions and perspectives

- The numerical procedure based on PALM and IBM is efficient in modeling the flow configuration of actively beating cilia (with the cilia movement imposed), and can be used in similar fluid-structure interactions problems.

- The Pleurobrachia does not move in the Stokes world; it acts like a pump, sucking and blowing fluids through the action of ctene rows. Detailed analysis of the flow and pressure fields can provide hints of what functional Nature has optimised.

- Perspectives: 3D simulations and complete interaction between freely beating hair (a “natural high lift device”) and the fluid.