Modeling and numerical simulations of swimmers

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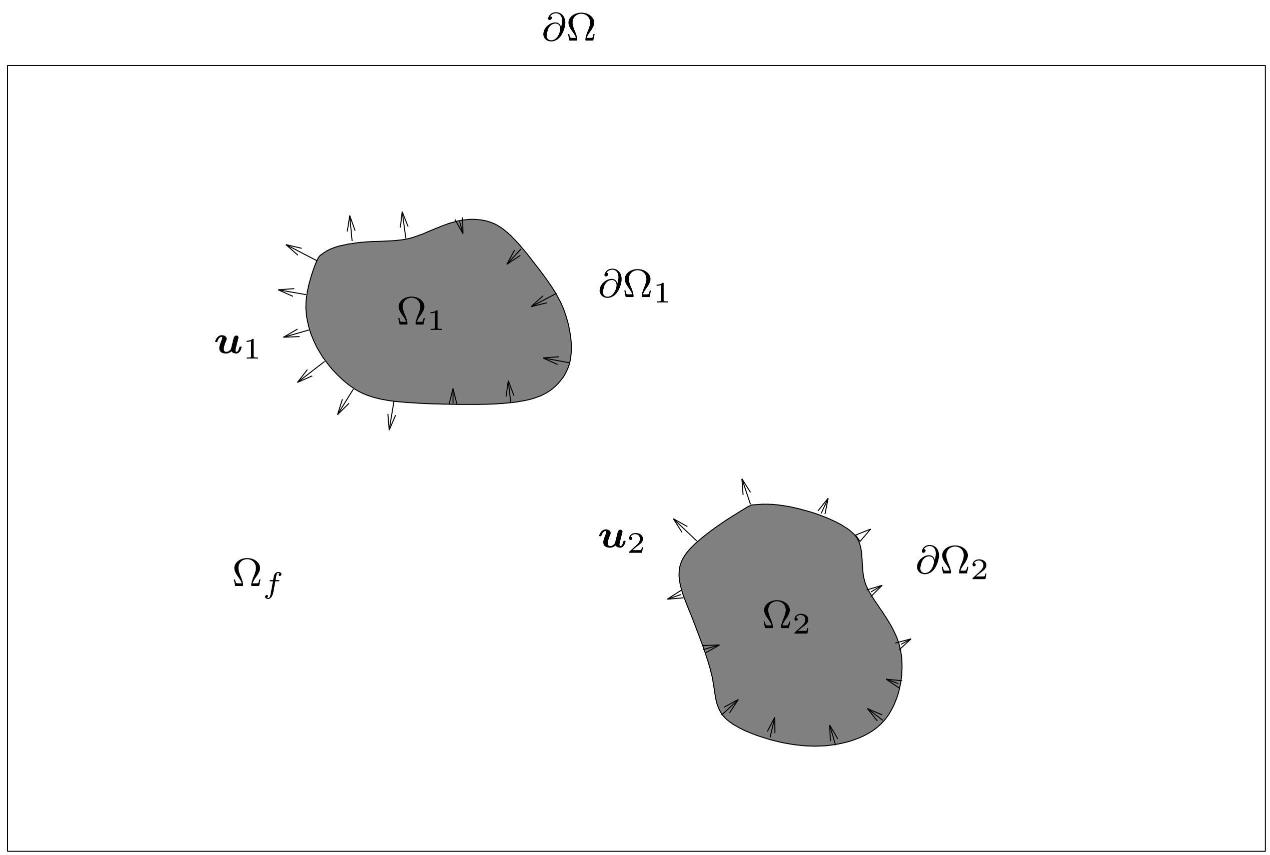
Flow configuration



Ω_i : Domain "body" i

Ω_f : Domain "fluid"

$\Omega = \Omega_f \cup \Omega_i$: Entire domain

Flow modeling

- **Classical model:** Navier-Stokes equations (incompressible): $Re = \dfrac{\rho U_{ref} L}{\mu}$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \frac{1}{Re}\Delta \boldsymbol{u} + \boldsymbol{g} \quad \text{in} \quad \Omega_f, \tag{1a}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0 \quad \text{in} \quad \Omega_f, \tag{1b}$$

$$\boldsymbol{u} = \boldsymbol{u}_i \quad \text{on} \quad \partial\Omega_i \tag{1c}$$

$$\boldsymbol{u} = \boldsymbol{u}_f \quad \text{on} \quad \partial\Omega \tag{1d}$$

Numerical resolution

Need of meshes that fit the body geometries

$\hookrightarrow$ Costly remeshing for moving and deformable bodies!!

Flow modeling

▶ **Penalization model:** penalized Navier-Stokes equations (incompressible):

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \frac{1}{Re}\Delta \boldsymbol{u} + \boldsymbol{g} + \lambda \sum_{1=1}^{N_s} \chi_i(\boldsymbol{u}_i - \boldsymbol{u}) \quad \text{in} \quad \Omega, \tag{2a}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0 \quad \text{in} \quad \Omega, \tag{2b}$$

$$\boldsymbol{u} = \boldsymbol{u}_f \quad \text{on} \quad \partial\Omega. \tag{2c}$$

$\hookrightarrow \lambda \gg 1$ penalization factor $\rightarrow$ Solution eqs (2) tends to solution eqs (1) *w.r.t.* $\varepsilon = 1/\lambda \rightarrow 0$.

$\hookrightarrow \chi_i = H(\phi_i)$ where H is Heaviside function and ϕ_i the signed distance function ($\phi_i(\boldsymbol{x}) > 0$ if $\boldsymbol{x} \in \Omega_i$, $\phi_i(\boldsymbol{x}) = 0$, if $\boldsymbol{x} \in \partial\Omega_i$, $\phi_i(\boldsymbol{x}) < 0$ else if).

$$\frac{\partial \phi_i}{\partial t} + (\boldsymbol{u}_i \cdot \nabla)\phi_i = 0.$$

Numerical resolution

No need of meshes that fit the body geometries

$\hookrightarrow$ Cartesian meshes

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Numerical approach | Method

- **Space:** Cartesian meshes,
  Centered FD 2nd order and upwind 3rd order for convective terms
  2^{nd} order penalization (immersed boundary like method)

- **Time:** 2^{nd} order Chorin scheme (Adams Bashforth/Crank Nicholson),
  Implicit penalization (larger λ)

$$\frac{\boldsymbol{u}^{(n+1)} - \boldsymbol{u}^{(n)}}{\Delta t} + \underbrace{(\boldsymbol{u}^{(n+\frac{1}{2})} \cdot \nabla)\boldsymbol{u}^{(n+\frac{1}{2})}}_{\text{Adams Bashforth}} = -\nabla p^{(n+\frac{1}{2}))} + \frac{1}{2\,Re}\underbrace{\left(\Delta \boldsymbol{u}^{(n+1)} + \Delta \boldsymbol{u}^{(n)}\right)}_{\text{Crank Nicholson}} + \boldsymbol{g}$$

$$+\lambda \sum_{1=1}^{N_s} \chi_i{}^{(n+1)}(\boldsymbol{u}_i{}^{(n+1)} - \boldsymbol{u}^{(n+1)}),$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u}^{(n+1)} = 0$$

$$(\boldsymbol{u}^{(n+\frac{1}{2})} \cdot \nabla)\boldsymbol{u}^{(n+\frac{1}{2})} = \frac{3}{2}(\boldsymbol{u}^{(n)} \cdot \nabla)\boldsymbol{u}^{(n)} - \frac{1}{2}(\boldsymbol{u}^{(n-1)} \cdot \nabla)\boldsymbol{u}^{(n-1)}$$

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Numerical approach | Method

- **Chorin :** prediction (2nd order)

$$\frac{\boldsymbol{u}^{(*)} - \boldsymbol{u}^{(n)}}{\Delta t} = -\left[(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}\right]^{(n+\frac{1}{2})} - \nabla q + \frac{1}{2\,Re}\left(\Delta\boldsymbol{u}^{(*)} + \Delta\boldsymbol{u}^{(n)}\right)$$

$$A\boldsymbol{u}^{(*)} = \boldsymbol{b}\left(\boldsymbol{u}^{(n)},\, \boldsymbol{u}^{(n-1)}\right)$$

- **Chorin :** correction $\qquad \Delta\psi^{(n+1)} = \nabla\cdot\boldsymbol{u}^{(*)}$

$$\widetilde{\boldsymbol{u}}^{(n+1)} = \boldsymbol{u}^{(*)} - \nabla\psi^{(n+1)}$$

$$\widetilde{p}^{(n+1)} = q + \frac{\psi^{(n+1)}}{\Delta t} - \frac{\Delta t}{2\,Re}\Delta\psi^{(n+1)}$$

- **Compute body motion :**

$$\boldsymbol{u}_i^{(n+1)} = f(\widetilde{\boldsymbol{u}}^{(n+1)}, \widetilde{p}^{(n+1)}) \text{ and } \chi_i^{(n+1)} = \chi_i^{(n)} - \Delta t(\widetilde{\boldsymbol{u}}^{(n+1)}\cdot\nabla)\chi_i^{(n)}$$

- **Penalization step :** $\frac{\boldsymbol{u}^{(n+1)} - \widetilde{\boldsymbol{u}}^{(n+1)}}{\Delta t} = \lambda\sum_{1=1}^{N_s}\chi_i{}^{(n+1)}(\boldsymbol{u}_i{}^{(n+1)} - \boldsymbol{u}^{(n+1)})$

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Numerical approach | Method

▶ **Compute body motion**

$$\boldsymbol{u}_i = \overline{\boldsymbol{u}}_i + \widehat{\boldsymbol{u}}_i + \widetilde{\boldsymbol{u}}_i$$

with:

$\overline{\boldsymbol{u}}_i$ translation velocity

$\widehat{\boldsymbol{u}}_i$ rotation velocity

$\widetilde{\boldsymbol{u}}$ deformation velocity (imposed for the swim)

$\hookrightarrow$ Compute forces $\boldsymbol{F}_i$ and torques $\boldsymbol{\mathcal{M}}_i$

$$m\frac{\mathrm{d}\overline{\boldsymbol{u}}_i}{\mathrm{d}t} = \boldsymbol{F}_i + m\boldsymbol{g}, \qquad \overline{\boldsymbol{u}}_i \quad \text{translation velocity,} \quad m \quad \text{mass}$$

$$\frac{\mathrm{d}J\boldsymbol{\Omega}_i}{\mathrm{d}t} = \boldsymbol{\mathcal{M}}_i, \qquad \boldsymbol{\Omega}_i \quad \text{angular velocity,} \quad J \quad \text{inertia matrix}$$

Rotation velocity $\widehat{\boldsymbol{u}}_i = \boldsymbol{\Omega}_i \times \boldsymbol{r}_G$ with $\boldsymbol{r}_G = \boldsymbol{x} - \boldsymbol{x}_G$ ($\boldsymbol{x}_G$ center of mass).

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Numerical approach | Method

▸ **Classic way**

Stress tensor $\mathbb{T}(\boldsymbol{u},\, p) = -p\mathbb{I} + \frac{1}{Re}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T)$ and n outward normal unit vector at s_i:

$$\boldsymbol{F}_i = -\int_{\partial\Omega_i} \mathbb{T}(\boldsymbol{u},\, p)\, \boldsymbol{n}\, \mathrm{d}\boldsymbol{x},$$

$$\boldsymbol{\mathcal{M}}_i = -\int_{\partial\Omega_i} \mathbb{T}(\boldsymbol{u},\, p)\, \boldsymbol{n} \times \boldsymbol{r}_G\, \mathrm{d}\boldsymbol{x}.$$

Evaluation of forces and torques

Cartesian mesh: no direct acces to $\partial\Omega_i$

$\hookrightarrow$ Not easy evaluation ....

Numerical approach | Method

▶ **Other way** : Arbitrarily domain $\Omega_{f_i}(t)$ surrounding body i.

Forces:

$$\boldsymbol{F}_i = -\frac{\mathrm{d}}{\mathrm{d}t}\int_{\Omega_{f_i}(t)} \boldsymbol{u}\,\mathrm{d}V + \int_{\partial\Omega_{f_i}(t)} (\mathbb{T} + (\boldsymbol{u}-\boldsymbol{u}_i)\otimes\boldsymbol{u})\,\boldsymbol{n}\,\mathrm{d}S - \int_{\partial\Omega_i(t)} ((\boldsymbol{u}-\boldsymbol{u}_i)\otimes\boldsymbol{u})\,\boldsymbol{n}\,\mathrm{d}S.$$

Torques:

$$\boldsymbol{\mathcal{M}}_i = -\frac{\mathrm{d}}{\mathrm{d}t}\int_{\Omega_{f_i}(t)} \boldsymbol{u}\times\boldsymbol{r}_G\,\mathrm{d}V + \int_{\partial\Omega_{f_i}(t)} (\mathbb{T} + (\boldsymbol{u}-\boldsymbol{u}_i)\otimes\boldsymbol{u})\,\boldsymbol{n}\times\boldsymbol{r}_G\,\mathrm{d}S - \int_{\partial\Omega_i(t)} ((\boldsymbol{u}-\boldsymbol{u}_i)\otimes\boldsymbol{u})\,\boldsymbol{n}\times\boldsymbol{r}_G\,\mathrm{d}S.$$

Evaluation of forces and torques

The term onto $\partial\Omega_i$ vanishes in our case (no transpiration)

$\hookrightarrow$ Easy evaluation!

Numerical approach | Method

- **Numerical resolution of Navier-Stokes equations (Cartesian mesh+Chorin)**

Developments and Experiments using Plafrim cluster

- Large scale 3D problems: more than 100 millions dofs

$\hookrightarrow$ Required parallel code

$\Rightarrow$ One solution: Message Passing Interface (MPI)

$\Rightarrow$ Other solution with higher abstraction level (more simple):

Portable, Extensible Toolkit for Scientific Computation (PETSc)

`http://www.mcs.anl.gov/petsc/petsc-as/`

$\hookrightarrow$ PETSc gives:

$\Rightarrow$ structures for parallelism (DA *Distributed Arrays* to manage cartesian meshes)

$\Rightarrow$ librairies to solve linear systems in parallel (KSP *Krylov Subspace methods*)

F-GMRES, preconditioner ASM with ILU on each subdomain

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Fish like swimming | Fish motion

▶ **Body velocity i:**

$$\boldsymbol{u}_i = \overline{\boldsymbol{u}}_i + \widehat{\boldsymbol{u}}_i + \widetilde{\boldsymbol{u}}_i.$$

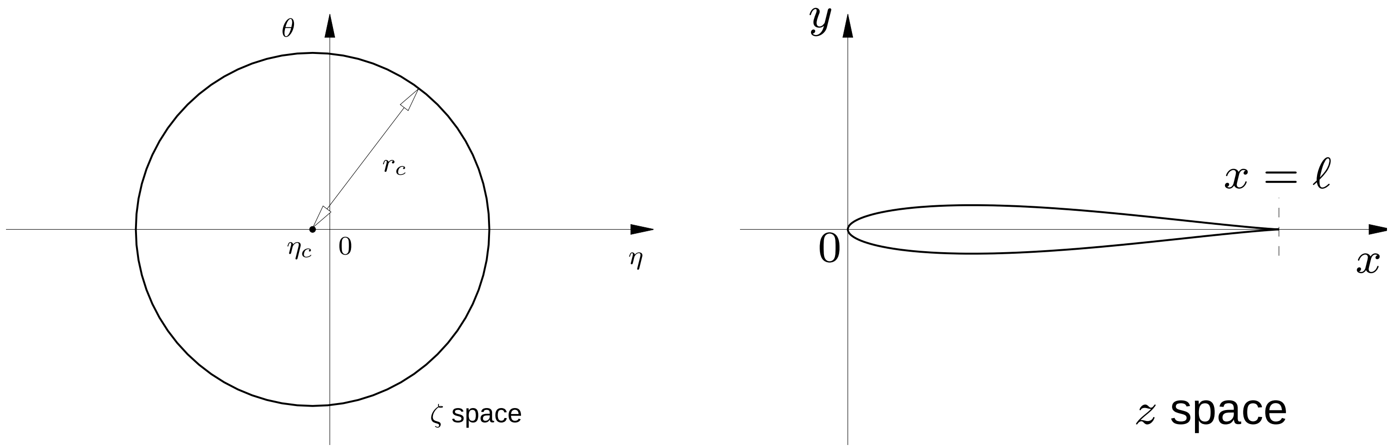
- Translation velocity $\overline{\boldsymbol{u}}_i$ is computed using forces $\boldsymbol{F}$
- Rotation velocity $\widehat{\boldsymbol{u}}_i$ is computed using torques $\boldsymbol{\mathcal{M}}$
- Deformation velocity $\widetilde{\boldsymbol{u}}_i$ is imposed for the swim

▷ Take care to not add artificial forces and torques!

1. Impose any backbone deformation,
2. Subtract body mass center motion due to deformation,
3. Rotate the body by the opposite angle generate by deformation,
4. Homothety for mass conservation

Fish like swimming | Steady fish shape

- **2D steady shape:** airfoil like profile



(a) Original shape (b) Steady shape

Fig. : *Sketch of the Karman-Trefftz transform. The z space is transformed to fit $0 \le x_s \le \ell$*

$$z = n \frac{\left(1+\frac{1}{\zeta}\right)^n + \left(1-\frac{1}{\zeta}\right)^n}{\left(1+\frac{1}{\zeta}\right)^n - \left(1-\frac{1}{\zeta}\right)^n},$$

$\Rightarrow$ **Only 3 parameters $\boldsymbol{b} = (\eta_c,\ \alpha,\ \ell)^T$**

$\triangleright$ $\alpha = (2-n)\pi$: tail angle

$\triangleright$ $\eta_c < 0$ circle center

$\triangleright$ $\ell > 0$ fish length ($\ell = 1$)

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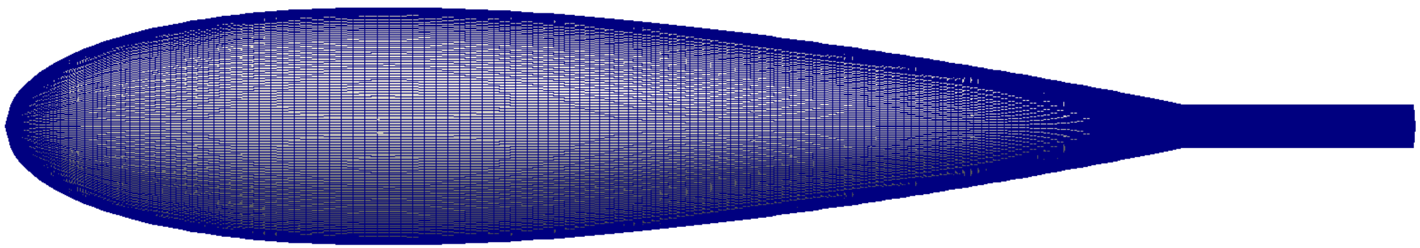
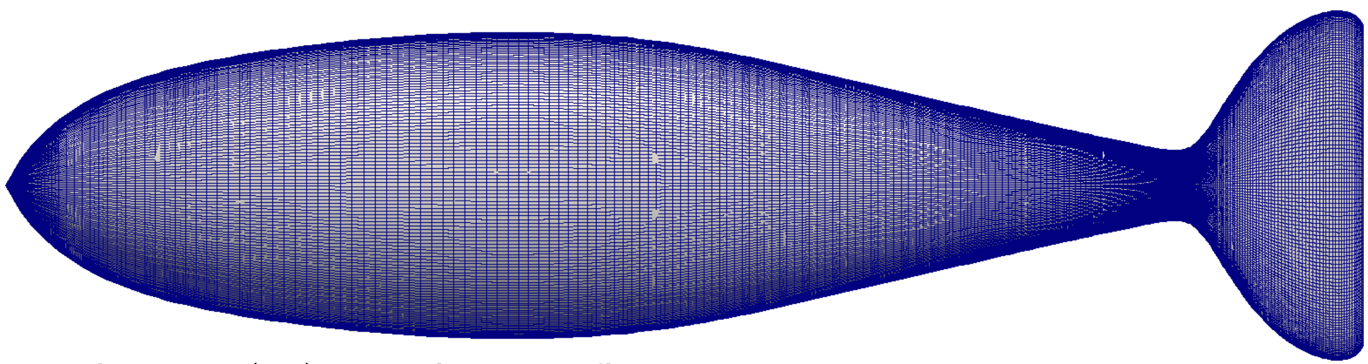
Fish like swimming | Steady fish shape

- **3D steady shape:** ellipses centered on the backbone x_i, with axis $y(x_i)$ and $z(x_i)$.



$\hookrightarrow$ 2D shape: $y(x_i)$ is airfoil profil (+ tail)



$\hookrightarrow$ 3D shape: $z(x_i)$ B-splines profil

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Fish like swimming | Swimming shape

$\hookrightarrow$ Backbone deformation in plan (x, y): $y(x,\, t) = (c_1 x + c_2 x^2)\sin(2\pi(x/\lambda + ft))$.

$\hookrightarrow$ 2D periodic, no artificial forces and torques,

$\hookrightarrow$ 3D each ellipse is orthogonal to the backbone $\Rightarrow$ mass conservation

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Fish like swimming | Swimming shape

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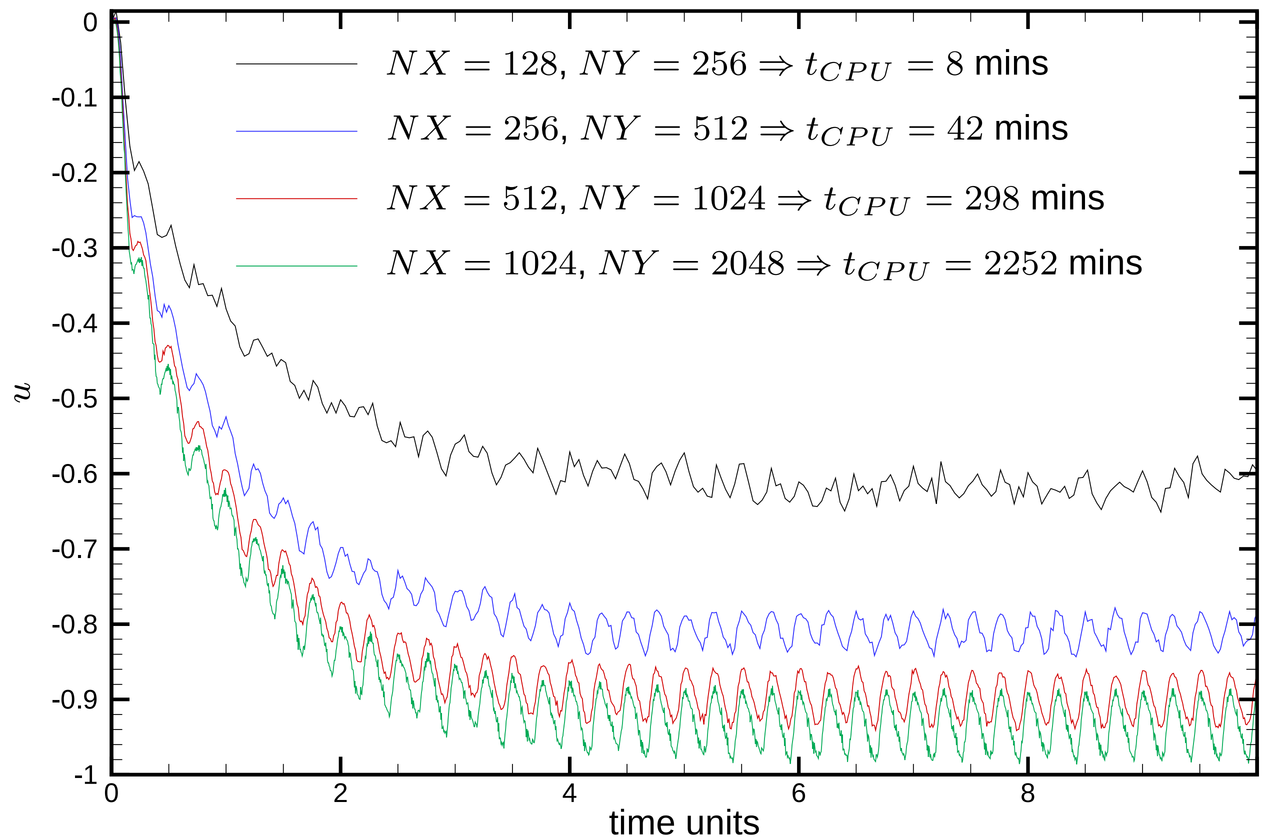
Fish like swimming | Convergence study

- **Complex flow (deformable and moving body) $\Rightarrow$ convergence study (2D)**

  Parameter: u velocity depends on the forces, the torques, the mesh, ...



$\Rightarrow NX = 512$ and $NY = 1024$ seems good balance "precision vs.computation time".

$\hookrightarrow \Delta X = \Delta Y = 1/128$ are chosen in following simulations

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Fish like swimming | Simulation

2D fish $Re = 1000$.

Fish like swimming | Simulation

3D fish $Re = 1000$*. Mesh* $1024 \times 128 \times 256 \approx 33 \cdot 10^6$ *nodes* $\Rightarrow 130 \cdot 10^6$ *unknowns.*

$\Rightarrow$ 3D and 2D wakes behavior are different

`S.Kern and P. Koumoutsakos, J Exp. Biology` **`209`**`, 2006.`

Fish like swimming | Turbulence simulation

Turbulence modeling: smagorinsky LES $Re = 10^6$

$\hookrightarrow$ Regulation of frequency and tail amplitude to reach a target swimming velocity $u_\tau = 0.56$.

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Fish like swimming | Turbulence simulation

Turbulence modeling: smagorinsky LES $Re = 10^6$

$\hookrightarrow$ Regulation of frequency and tail amplitude to reach a target swimming velocity $u_\tau = 0.56$.

The optimized frequency $f \approx 1.1$ and double amplitude $A \approx 0.14$.

$\Rightarrow$ The Strouhal number $St = \frac{f\,A}{u_\tau} \approx 0.275$

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Fish like swimming | Gray paradox?

Gray's paradox [1] :

"the power required for a dolphin of length $1.82m$ to swim at a speed of $10.1m/s$ is about seven times the muscular power available for propulsion (swimming more efficient than rigid body towed at same velocity)

$\hookrightarrow$ Paradox contested (J. Lighthill [2]) : fish power 3X higher

$\hookrightarrow$ Paradox "confirmed" experimentally at MIT (robot bluefin tuna) by Barret *et al.* [3]

[1] Gray J. (1936) : Studies in animal locomotion. VI. The propulsive power of the dolphin, *J. Exp. Biol.* **13** pp. 192-199.

[2] Lighthill, M.J. (1971) : Large amplitude elongated-body theory of fish locomotion, *Proc. R. Soc. Mech. B.* **179** pp. 125-138.

[3] Barrett, D.S., Triantafyllou, M.S., Yue, D.K.P., Grosenbauch, M.A., Wolfgang, M.J. (1999) : Drag reduction in fish-like locomotion, *J. Fluid Mech.* **392** pp. 182-212.

Fish like swimming | Gray paradox?

- **Power**

$$P(t) = \frac{\partial}{\partial t}\int_{\Omega_f} \frac{u^2}{2}\,\mathrm{d}\Omega + \frac{1}{Re}\int_{\Omega_f} \sigma'_{ij}\frac{\partial u_i}{\partial x_j},\mathrm{d}\Omega.$$

- **Propulsive index**

$$I_p = \frac{P_{tow}}{P_{swim}}.$$

- In turbulent case $Re = 10^6$ with $St = 0.275 \quad \Rightarrow \quad I_p = 0.35$, *i.e.* $P_{tow} < P_{swim}$

$\hookrightarrow$ No numerical evidence of Gray's paradox

$\hookrightarrow$ Possible reasons:

– is does no exist!

– numerical errors: LES model, cartesian meshes (boundary layers?) $\rightarrow$ error friction?, ..

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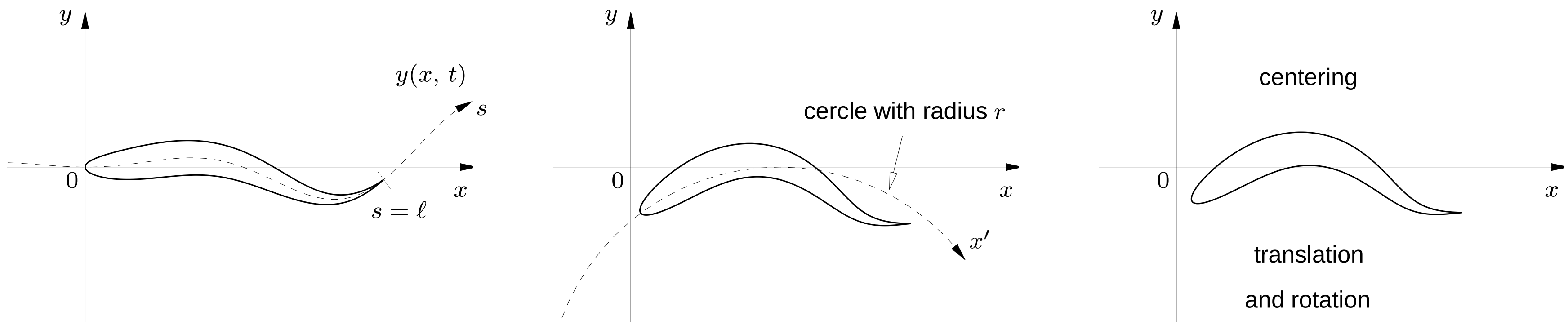
Fish like swimming | Maneuvers

Example: predator/prey $\Rightarrow$ reach food

Method: add mean curvature r



(c) Swimming shape (d) Maneuvering shape (e) Real motion shape

Fig. : *Sketch of swimming and maneuvering shape.*

Question: adaptation of $r(t)$?

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Fish like swimming | Maneuvers

Idea: adapt r using "angle of vision" θ_f, i.e. $r = r(\theta_f)$:

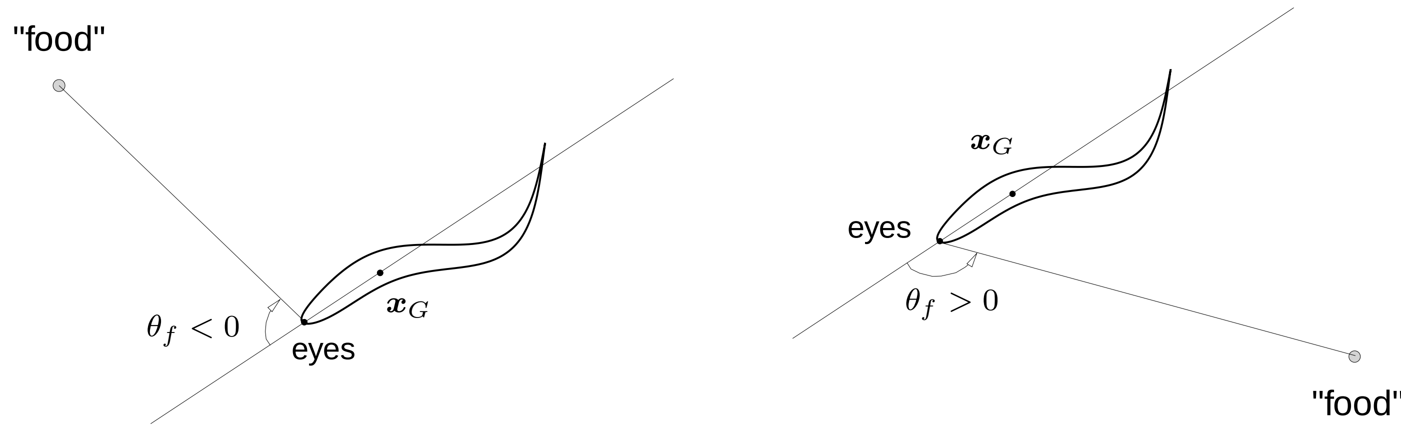

Fig. : *Sketch of the oriented food angle of vision.*

$$r(\theta_f) = \begin{cases} \infty & \text{if } \theta_f = 0, \\ \overline{r} & \text{if } \theta_f \geq \overline{\theta_f}, \\ -\overline{r} & \text{if } \theta_f \leq -\overline{\theta_f}, \\ \overline{r}\left(\dfrac{\overline{\theta}}{\theta_f}\right)^2 & \text{otherwise.} \end{cases}$$

We impose $|r| \geq \overline{r}$ and $|\theta_f| \geq \overline{\theta_f}$. We chose arbitrarily $\overline{r} = 0.5$ and $\overline{\theta} = \pi/4$.

Fish like swimming | Maneuvers

2D fish $Re = 1000$

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Fish like swimming | Maneuvers

3D fish $Re = 1000$. *Mesh* $512 \times 128 \times 512 \approx 33 \cdot 10^6$ *nodes* $\Rightarrow 130 \cdot 10^6$ *unknowns.*

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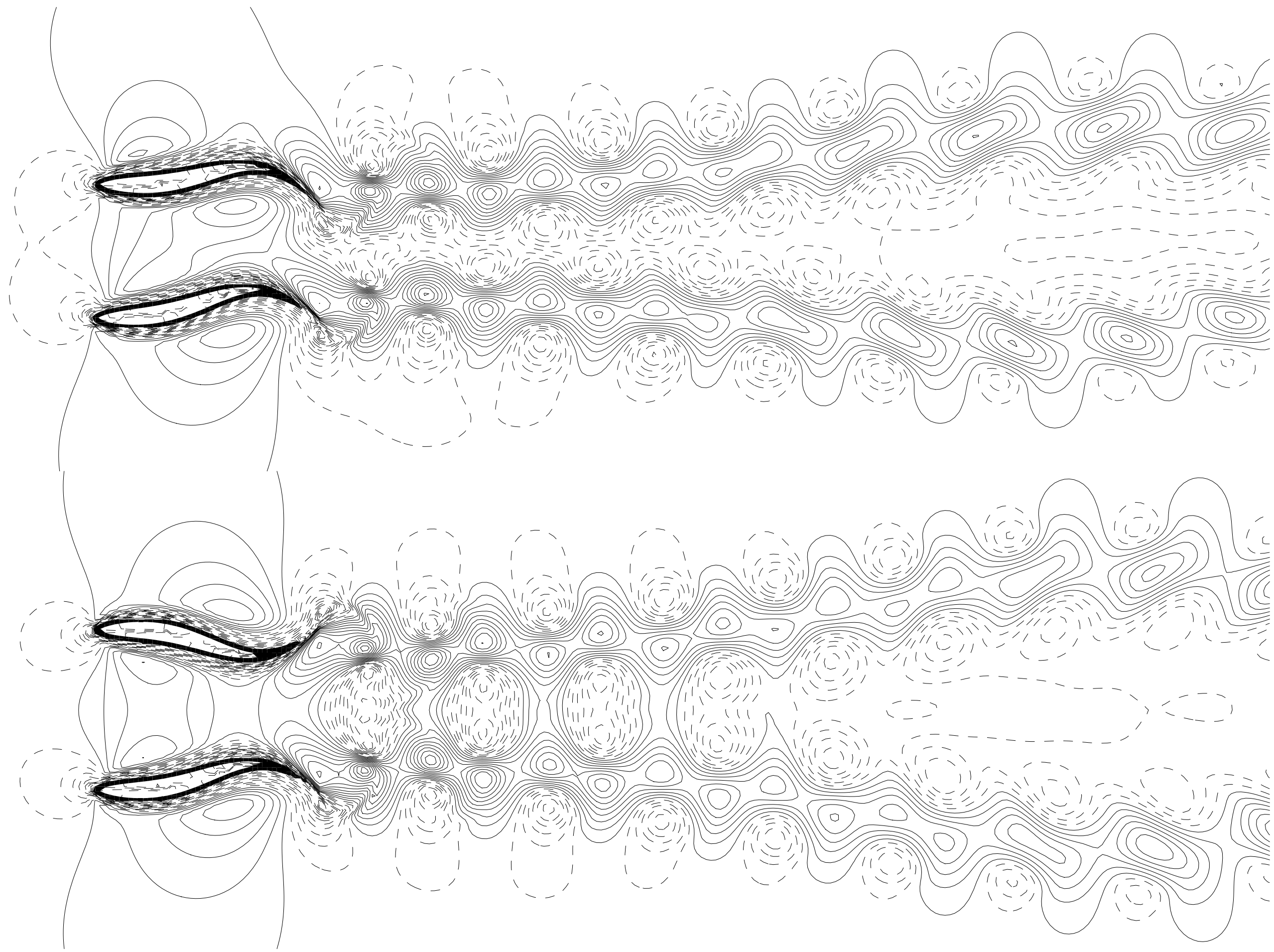
Fish like swimming | Schooling

- **Configuration:** school limited to 3 fishes

↪ **Preliminary study** 2 fishes with parallel swim

Velocity u
Phase

Velocity u
Anti-phase



Fish like swimming | Schooling

- **Observation:** existence of a zone in the wake where flow has same velocity sign than fishes velocities

- **Idea:** put a third fish in this zone with "potential benefits"

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Fish like swimming | Schooling

- **Observation:** existence of a zone in the wake where flow has same velocity sign than fishes velocities
- **Idea:** put a third fish in this zone with "potential benifits"

Anti-phase. $\Rightarrow$ Quite efficient.

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Fish like swimming | Schooling

- ▶ **Observation:** existence of a zone in the wake where flow has same velocity sign than fishes velocities
- ▶ **Idea:** put a third fish in this zone with "potential benifits"

Phase. $\Rightarrow$ Very efficient.

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Fish like swimming | Schooling

- **Goal:** save energy

↪ adapt velocity of the third fish

(regulation of tail amplitude A to reach same velocity than two other fishes)

	Phase				Anti-phase			
L D	0.4	0.5	0.6	0.7	0.4	0.5	0.6	0.7
1.5	15.0	16.3	11.1	7.1	6.8	6.9	9.8	7.1
2.0	10.1	14.5	9.8	6.0	6.8	6.1	9.8	6.0
2.5	8.4	13.6	9.0	5.1	6.7	5.3	9.0	5.1
3.0	15.0	15.1	6.9	5.0	5.2	5.1	7.0	3.2
3.5	5.2	13.2	6.2	2.2	4.9	5.0	6.2	0.5

Tab. : *Percentage of energy saved for the three fishes school in comparison with three independent fishes.* $Re = 10^3$.

The 3 fishes school can save an amount around 15% of total energy!!

Fish like swimming | Schooling

3D fishes $Re = 1000$. *Mesh* $1024 \times 128 \times 256 \approx 33 \cdot 10^6$ *nodes* $\Rightarrow 130 \cdot 10^6$ *unknowns.*
$\Rightarrow$ No efficient effect for 3^{rd} fish. 3D wake $\neq$ 2D wake (no inverted VK street)

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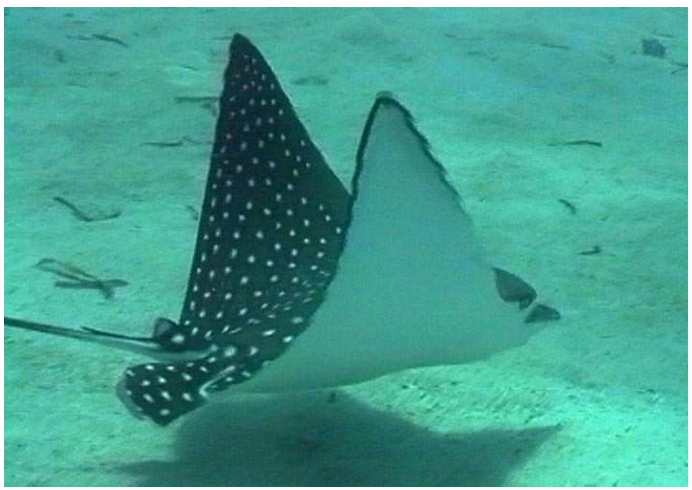
Fish like swimming | First ray model

Fish like swimming | First ray model

3D ray-like swimming with flapping wings at $Re = 10^4$.

Fish like swimming | Second ray model



Fish like swimming | Second ray model

3D ray-like swimming with flapping wings at $Re = 10^4$.

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Fish like swimming | Simplified Jellyfish model

Fish like swimming | Simplified Jellyfish model

3D jellyfish $Re = 1000$*. Mesh* $256 \times 256 \times 512 \approx 33 \cdot 10^6$ *nodes* $\Rightarrow 130 \cdot 10^6$ *unknowns.*

$\Rightarrow$ Velocity very close to 2D case (quasi axisymmetric)

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Other 3D simulations | Wind turbine

Wind turbine: photo

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Other 3D simulations | Wind turbine

Wind turbine: modeling (size 3m)

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Other 3D simulations | Wind turbine

Wind turbine: rotation (20 rpm)

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Other 3D simulations | Wind turbine

Wind turbine: numerical simulation (wind 3 m/s, $Re = 10^4$)

Mesh $350 \times 350 \times 350 \approx 42 \cdot 10^6$ *points* $\Rightarrow 170 \cdot 10^6$ *unknowns.*

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Other 3D simulations | Wind turbine

Wind turbine: numerical simulation (wind 3 m/s, $Re = 10^6$, Smagorinsky turbulence model)

Mesh $350 \times 350 \times 350 \approx 42 \cdot 10^6$ *points* $\Rightarrow 170 \cdot 10^6$ *unknowns.*

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Next ....

- **Fluid-Structure interactions & elasticity** (eulerian, post doc Thomas Milcent)

  $\hookrightarrow$ Model the tail/fins

  $\rightarrow$ Example: cylinder motion imposed by penalization with free motion of the "tail"

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