COMSOL CONFERENCE 2015 GRENOBLE

The Virtual Aquarium: Simulations of Fish Swimming

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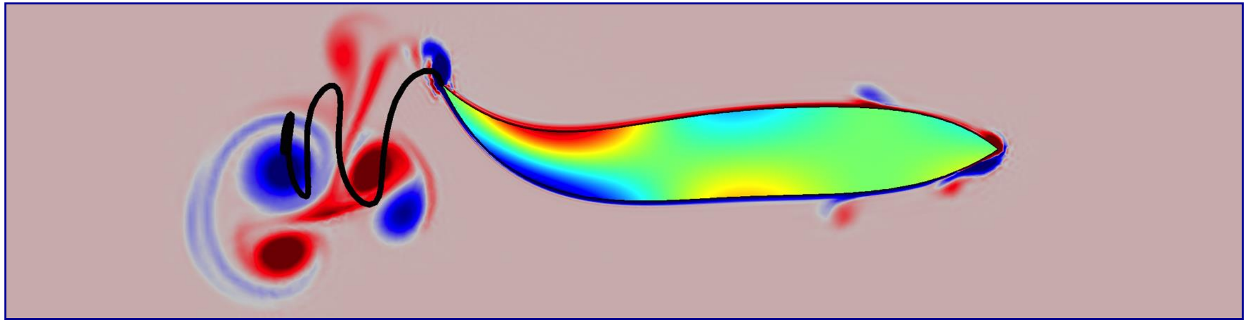


1. Swimming style

1.1 Some of traditional categories used to describe patterns of body undulation in fishes:

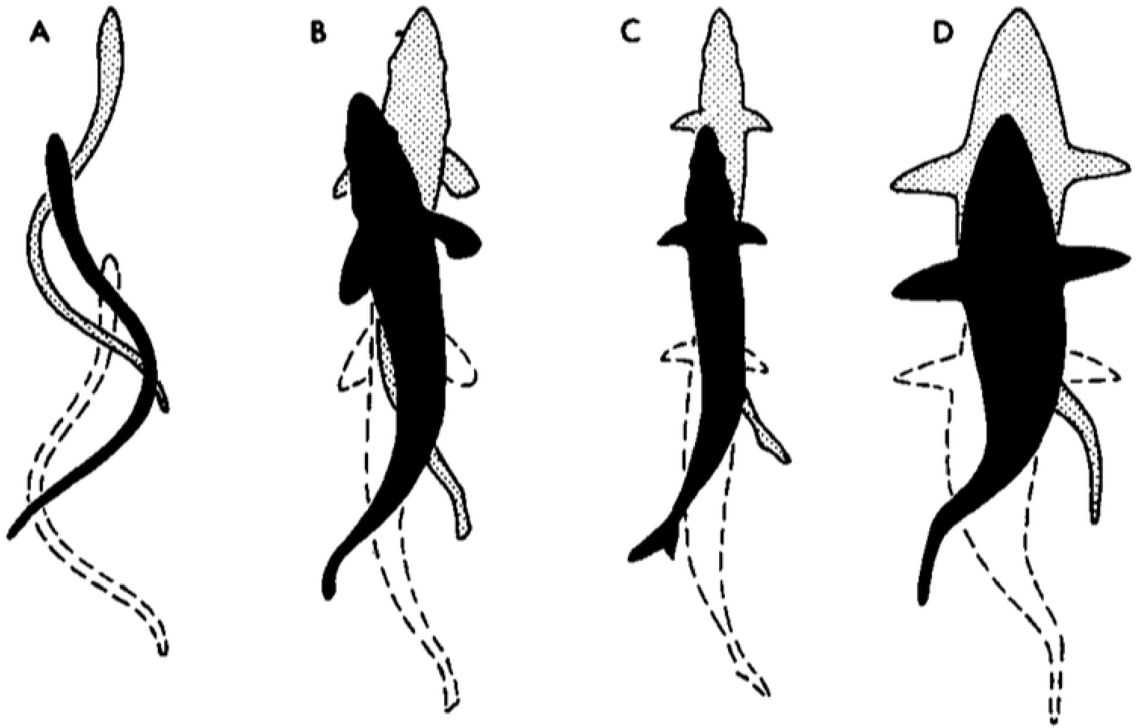
Anguilliform

Carangiform

Subcarangiform

Thunniform

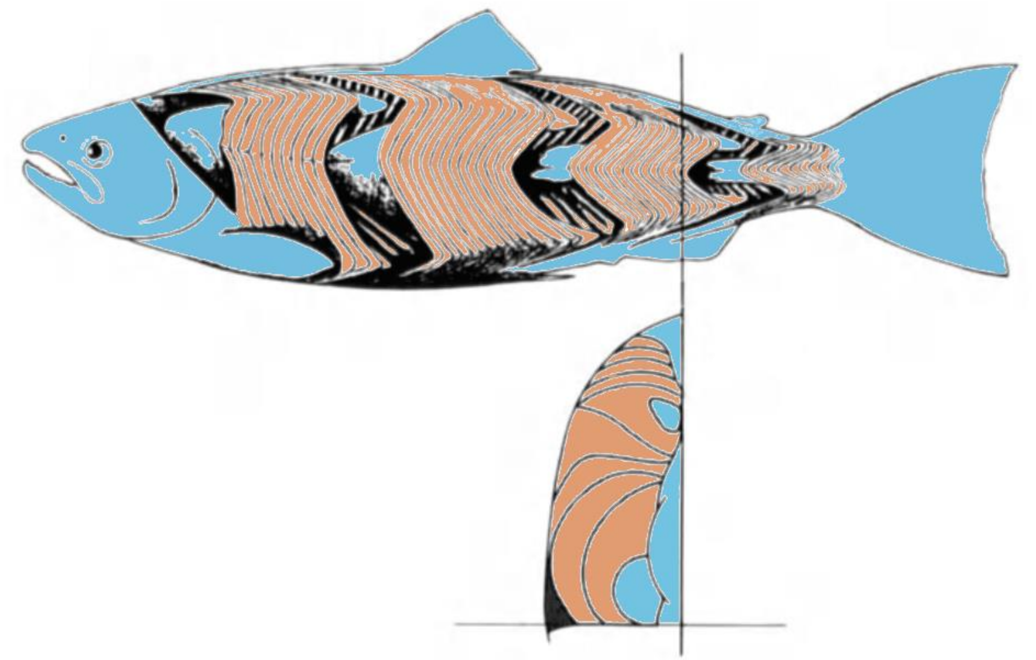
1.2 Patterns of 2D body undulation are very similar among fishes:



Anguilliform Subcarangiform Carangiform Thunniform

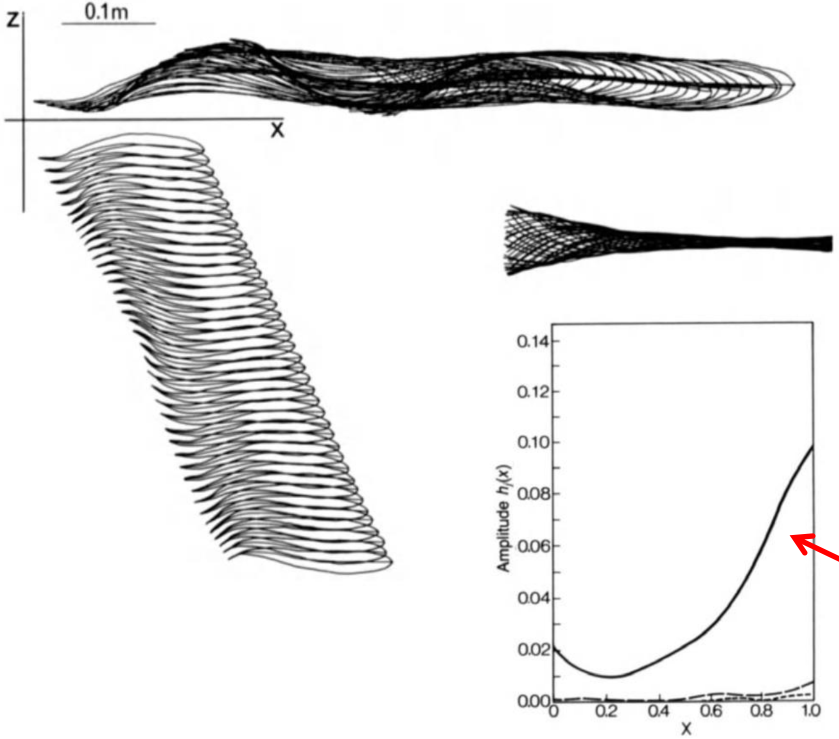
W.S. Hoar and D.J. Randall (Eds.)-Locomotion-Elsevier, Academic Press (1979), Fish Physiology Volume VII

1.3 The swimming engine of several types of fishes is composed by lateral muscle fibers, called *myotomes*. The complex architecture of myotomes is related to the movements of fish.



J. J. Videler. Fish Swimming, Springer-Science+Business Media, B.V., 1993.

1.4 Fish have been induced to swim against a water current at various speeds.

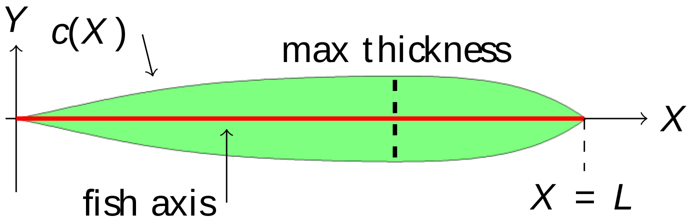


$$e(X) = \frac{4}{25\,L}X^2 - \frac{6}{25}X + \frac{1}{10}L$$

J. J. Videler. Fish Swimming, Springer-Science+Business Media, B.V., 1993.

1.5 Carangiform swimming style shows a traveling wave along the body;

Wave velocity: $c_o = \omega / \gamma$



Angular frequency

Wave number

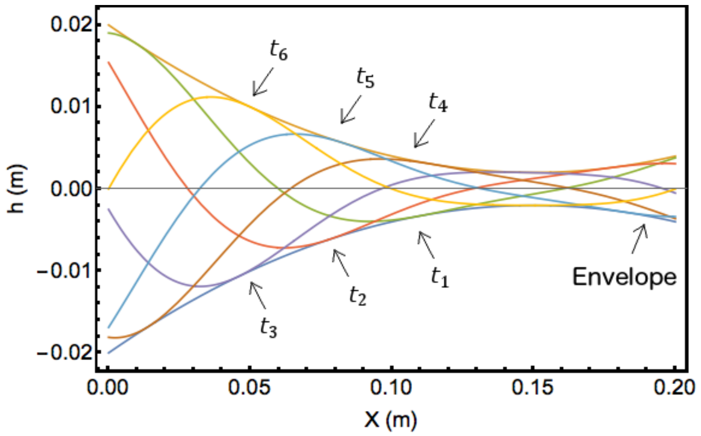
Activation time

$$h(X,t) = e(X)\, \sin(\gamma X + \omega t)\, (1 - \exp(-t/t_a))$$

Envelope

Traveling-wave

Time switch

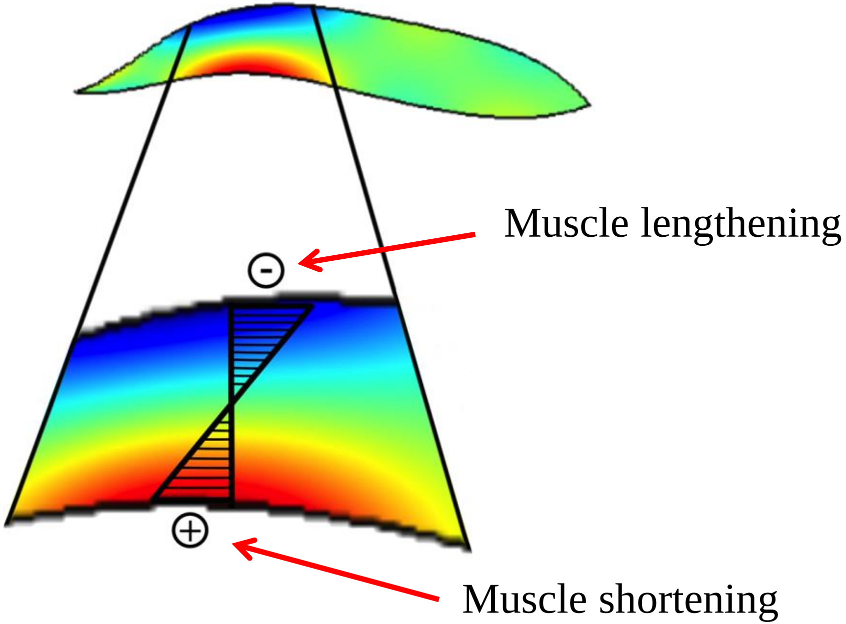


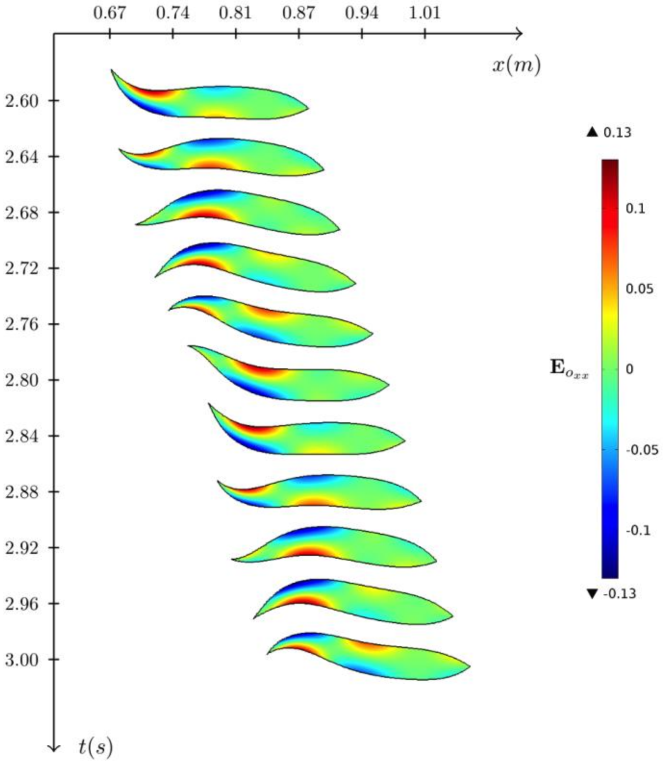
J. J. Videler. Fish Swimming, Springer-Science+Business Media, B.V., 1993.

1.6 The muscles action is modeled in Comsol assigning a distortion field to the solid body.

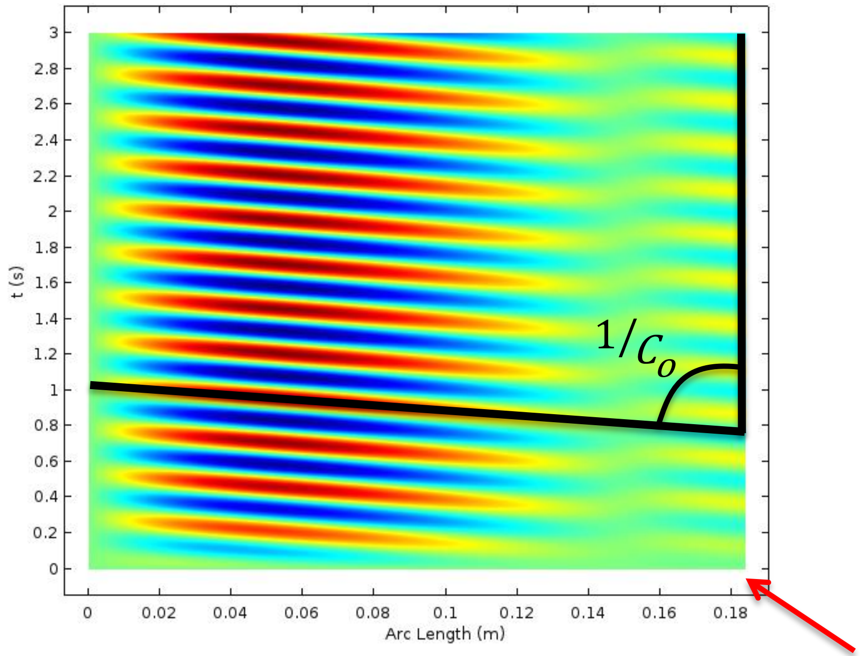
To define a swimming style, we first assign the function $h(X,t)$ and then derive the muscle driven distortions $\mathbf{E}^o_{xx}$.

$$h(X,t) \longrightarrow \mathbf{E}^o_{xx}(X,Y,t) = -Y\frac{\partial^2 h(X,t)}{\partial X^2}$$

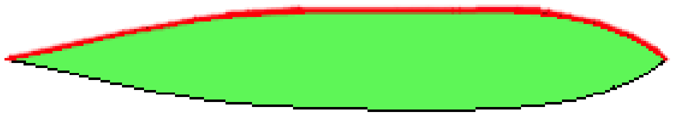




1.7 Traveling wave has velocity: $c_o = f\lambda$



$\mathbf{E}^o_{xx}$



Control parameters

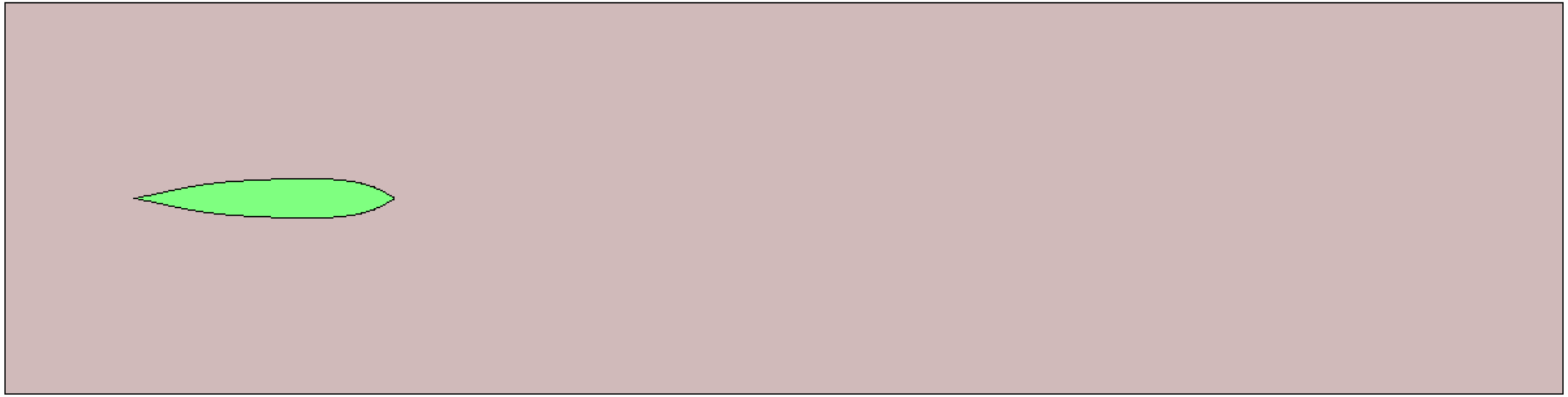
- Wave frequency $f = \dfrac{\omega}{2\pi}$
- Wavelength $\lambda = \dfrac{2\pi}{\gamma}$
- Activation Time t_a

2. Fish swimming

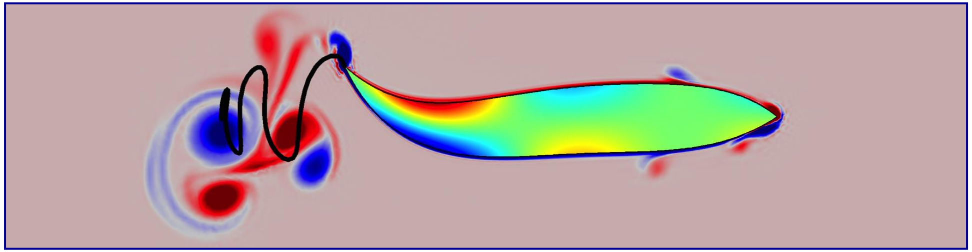
Real time; fluid speed and muscles contraction.

Slow motion 4x

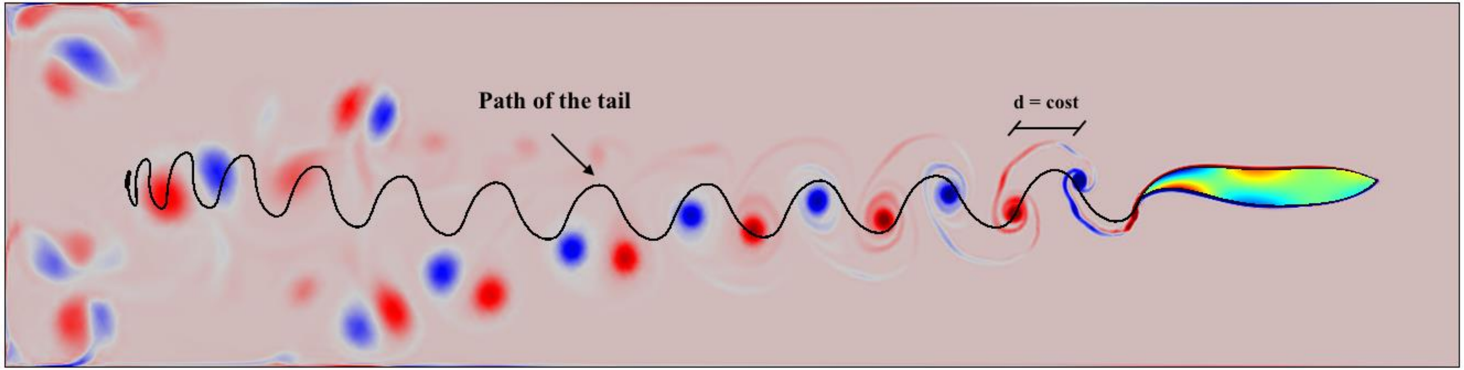
Slow motion 4x; Vortex field and muscles contraction.



2.1 Vortices are released at the end of every stroke.



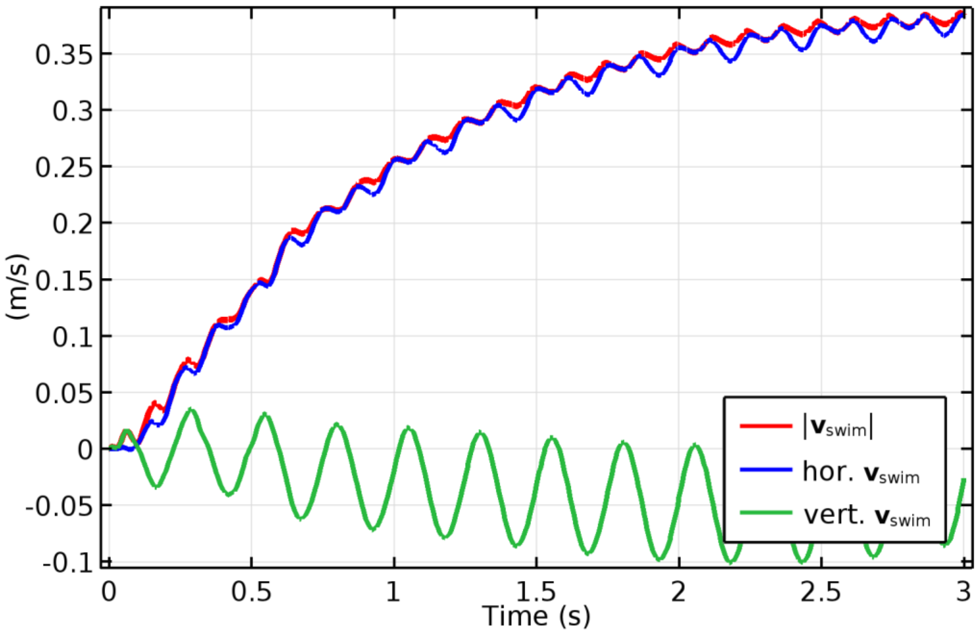
Mutual distances between vortices do not change:



2.2 Velocity realized at fish center of mass shows good accordance with empirical expected value, provided the fact that our simulations are 2D.

Empirical relation

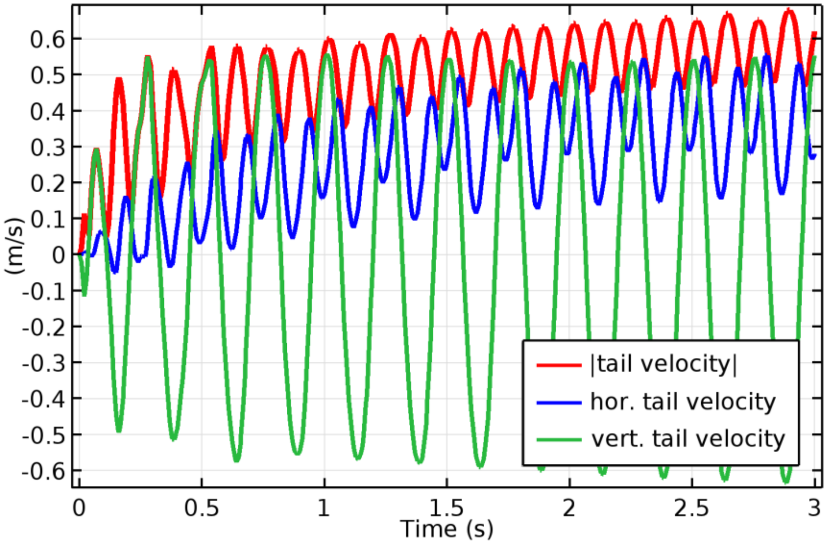
$$\frac{|\mathbf{v}_{swim}|}{L} = \alpha\, f$$

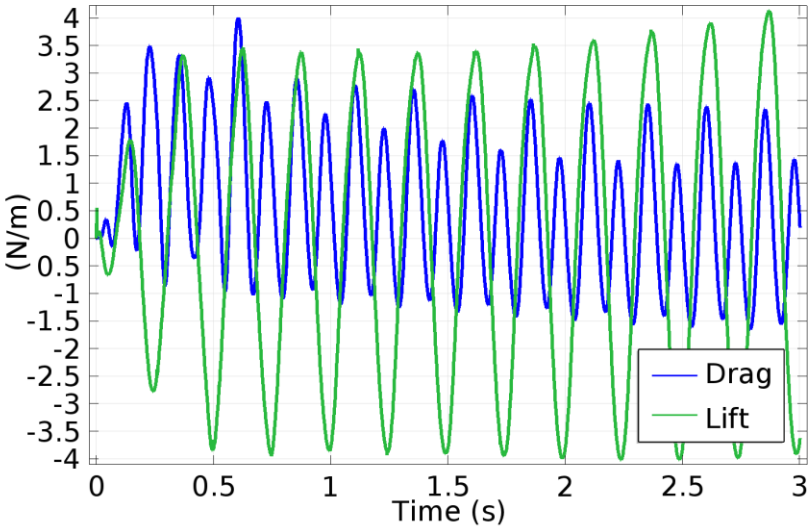


The contribution to the overall speed (red) comes essentially from the horizontal part.

2.3 Lift and drag forces are calculated integrating fluid stress on fish contour. There is great similarity between tail velocity components and lift and drag forces.

$$F_L = \int_{\partial\Omega_s} \Gamma\, \mathbf{n}_f \cdot \mathbf{e}_y \, ds; \quad F_D = \int_{\partial\Omega_s} \Gamma\, \mathbf{n}_f \cdot \mathbf{e}_x \, ds,$$





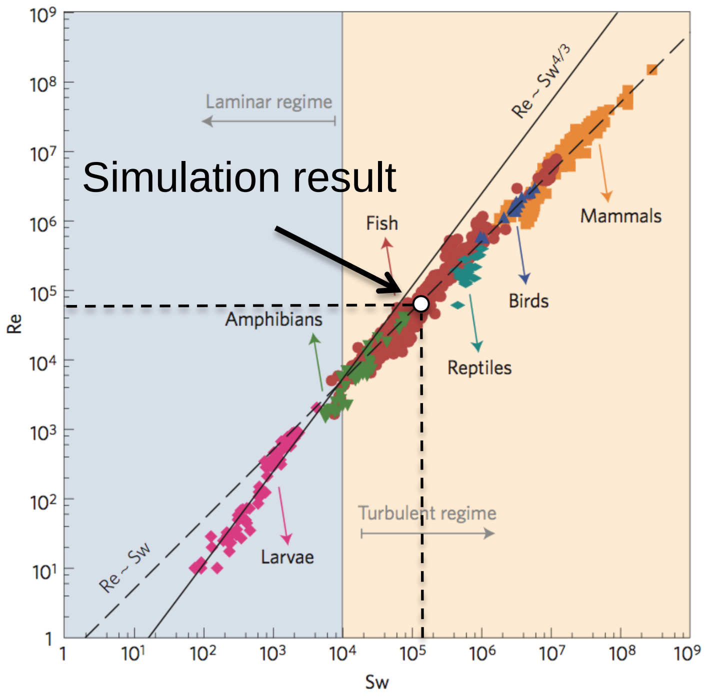
we have great oscillations for lift force and minor oscillations for drag force.

2.4 Animal motions are influenced by a relation between Reynolds number Re and transverse Reynolds number Sw .

$$Re = \frac{|\mathbf{v}_{swim}|\, L\, \rho_f}{\mu_f}, \quad Sw = \frac{A\,\omega\,\rho_f}{2\pi\,\mu_f}$$

$$Re \sim S_w$$

$$Re = 7.62 * 10^4 \quad S_w = 1.10 * 10^5$$



Gazzola, M., Argentina, M., & Mahadevan, L. (2014). Scaling macroscopic aquatic locomotion. *Nature Physics*. (2014)

3. Comsol settings

3.1 We need both moving mesh to solve the FSI for short time intervals, and re-meshing to track the long swimming path we aim at simulating.