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:
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.

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

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

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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 $E_{xx}^o$.

\[ h(X, t) \quad \rightarrow \quad E_{xx}^o(X, Y, t) = -Y \frac{\partial^2 h(X, t)}{\partial X^2} \]

Muscle shortening

Muscle lengthening
1.7 Traveling wave has velocity: \( c_o = f \lambda \)

Control parameters

- Wave frequency \( f = \frac{\omega}{2\pi} \)
- Wavelength \( \lambda = \frac{2\pi}{\gamma} \)
- Activation Time \( t_a \)

\( \text{E}^o_{xx} \)
2. Fish swimming

Real time; fluid speed and muscles contraction.

\[ f = 4 \text{ Hz}; \lambda = 0.2 \text{ m}; t_a = 0.2 \text{ s}. \]
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

\[ \frac{|v_{\text{swim}}|}{L} = \alpha f \]

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 $Sw$.

\[
Re = \frac{|v_{swim}| L \rho_f}{\mu_f}, \quad Sw = \frac{A \omega \rho_f}{2\pi \mu_f}
\]

\[
Re \sim Sw
\]

\[
Re = 7.62 \times 10^4 \quad Sw = 1.10 \times 10^5
\]

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.