Understanding Fish Propulsion through Fluid Simulations

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Objective and Research question

How can we optimize fish swimming behavior for highest efficiency under different flow conditions?

- Optimize non-dimensional swimming parameters
- Explore effect of **amplitude envelope** on **thrust** and **swimming efficiency**.
- Develop **optimal control methodology** to navigate complex flow conditions

Background and Fundamental Equations [1]

Strouhal number:

$$\mathrm{St} = \frac{fA}{U}$$

Reynolds number:

$$\mathrm{Re} = \frac{UL}{\nu}$$

Traveling wave:

$$y = A\sin(kx - \omega t)$$

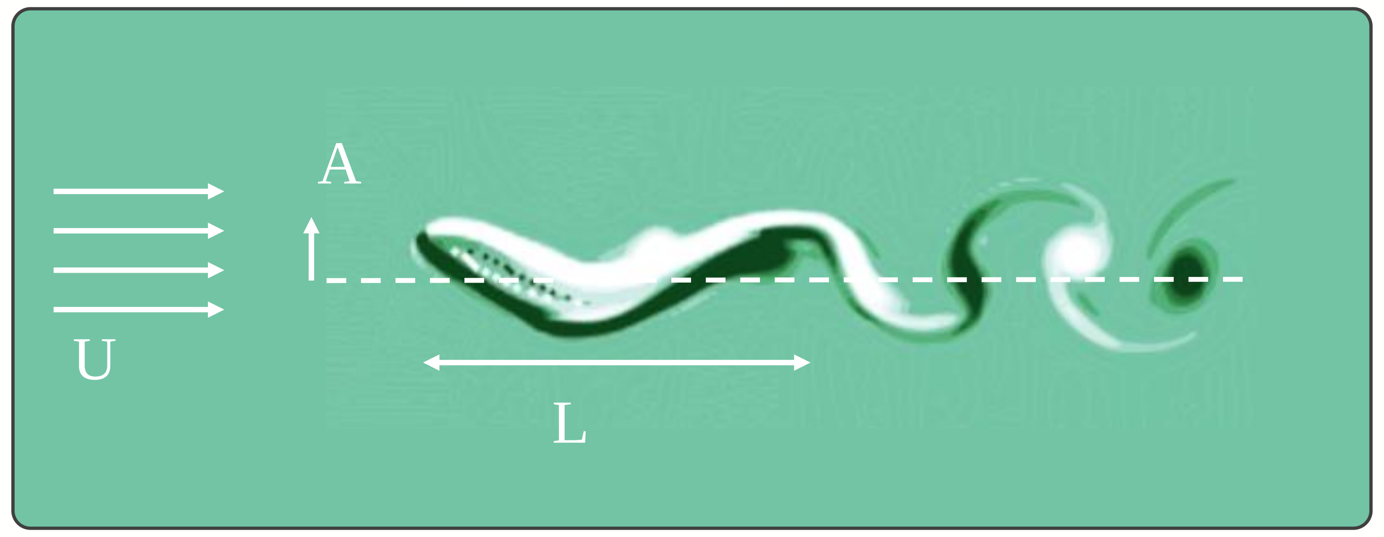
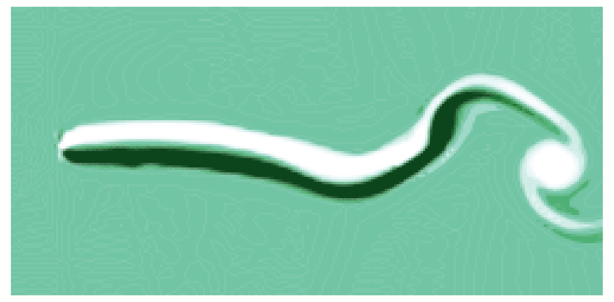


Fig 1. Fundamental variables for anguilliform swimming.

Amplitude Envelope:

Fish in nature oscillate tail more than the head (amplitude envelope)



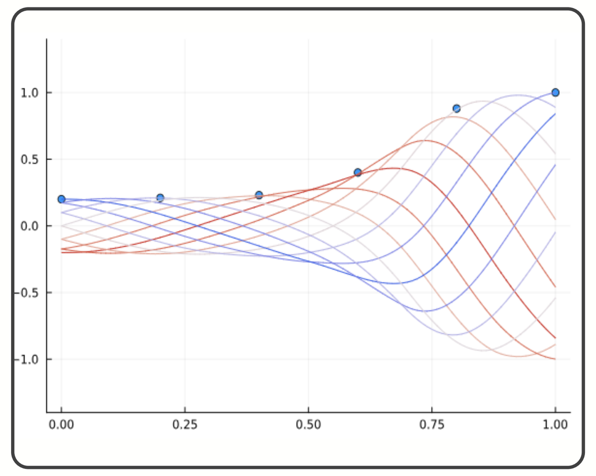


Fig 2. natural amplitude envelope

Preliminary Results

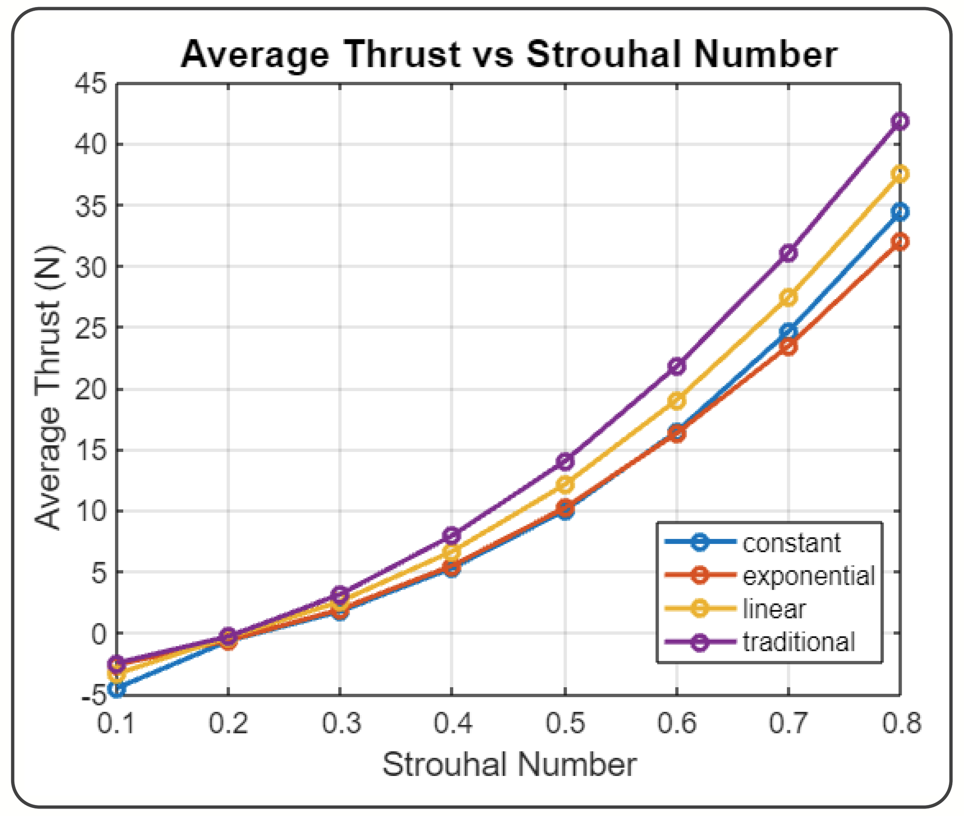


Fig 3. Average thrust vs. Strouhal number

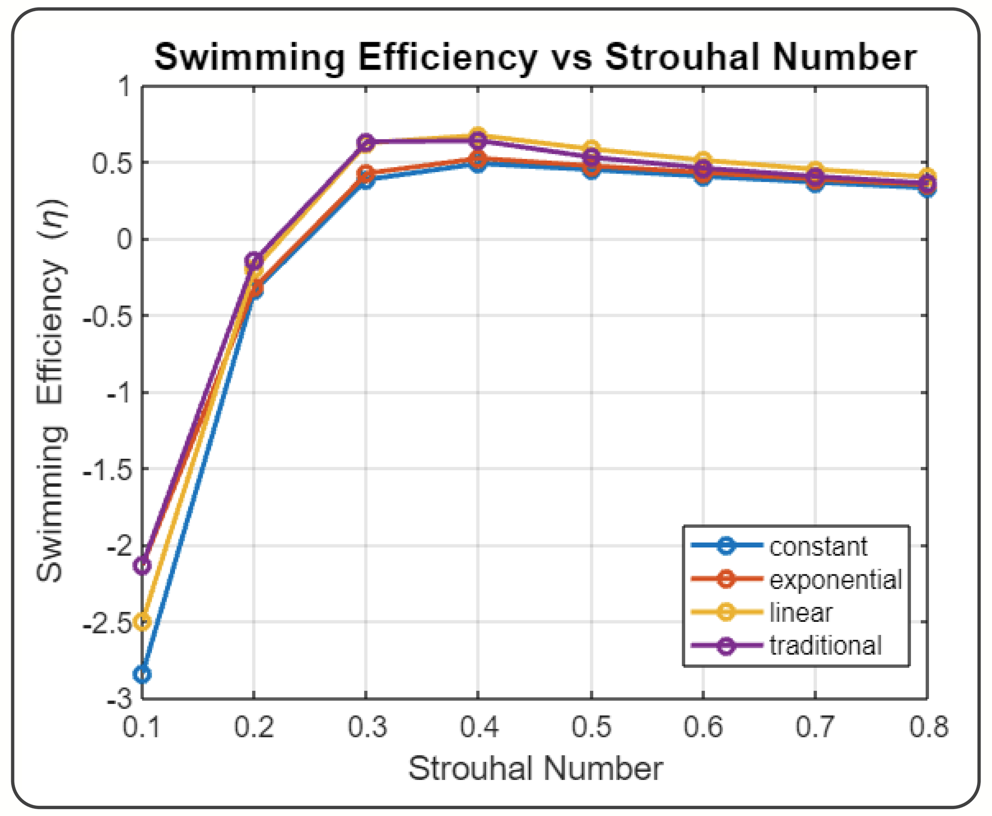


Fig 4. Efficiency vs. Strouhal number

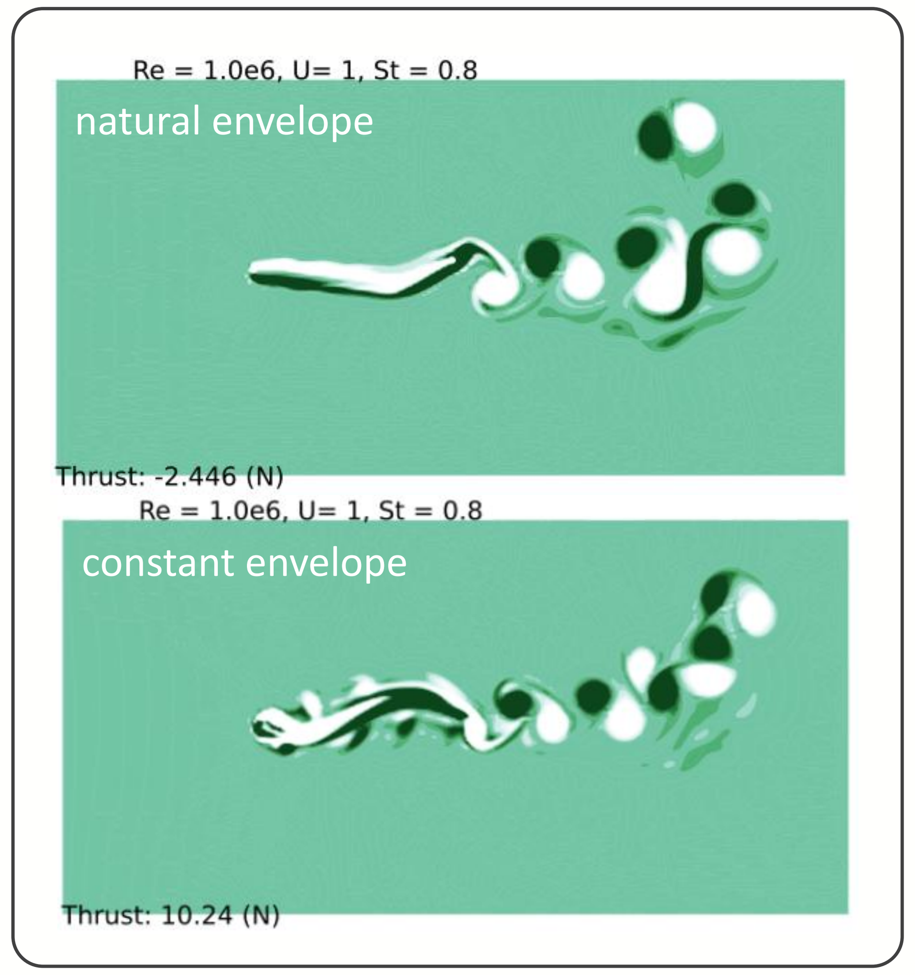


Fig 5. natural amplitude envelope prevents excess vorticities and increases efficiency

Table 1: Simulation results for natural envelope

St	$\bar{F}_x$ (N)	$\bar{F}_y$ (N)	KE Rate (W)	η
0.1	-2.48	-0.06	1.16	-2.13
0.2	-0.29	0.71	1.99	-0.14
0.3	3.15	1.11	4.99	0.63
0.4	7.96	1.23	12.48	0.64
0.5	14.04	0.74	26.52	0.53
0.6	21.83	-0.94	47.63	0.46
0.7	31.15	-4.54	77.16	0.40
0.8	41.93	-8.16	117.06	0.36

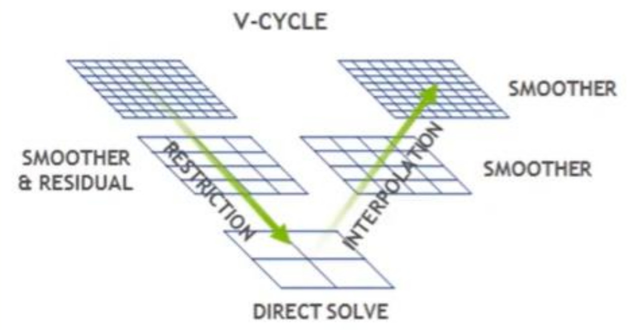
Table 2: Simulation results for linear envelope

St	$\bar{F}_x$ (N)	$\bar{F}_y$ (N)	KE Rate (W)	η
0.1	-3.36	-0.17	1.34	-2.50
0.2	-0.34	0.35	1.73	-0.20
0.3	2.57	0.89	4.13	0.62
0.4	6.66	1.29	9.89	0.67
0.5	12.14	0.96	20.82	0.58
0.6	19.07	-0.11	37.40	0.51
0.7	27.48	-1.66	61.13	0.45
0.8	37.50	-4.95	93.76	0.40

Methodology for Preliminary Work

Fluid solver: Waterlily boundary-immersion method solver in Julia language [2]

- Solves incompressible (divergence-free) Navier-Stokes Equations using Finite-volume approach with staggered velocity-pressure grid
- Solved using geometric multi-grid approach



Quantifying Swimming Efficiency:

$$\eta = \frac{\overline{T}\cdot U}{\dot{E}_{\text{flow}}}$$

$\overline{T}$ = Average thrust force

U = fish swimming velocity

$\dot{E}_{\text{flow}}$ = total kinetic energy fish movement adds to water per unit time

$$\mathrm{KE}_{\text{flow}}(t) = \frac{1}{2}\rho\sum_{i,j}\left[(u_{i,j}-U)^2 + v_{i,j}^2\right]\Delta A$$

Preliminary Results

- The results suggest that either a **linear** or **natural amplitude envelope** with a **Strouhal number of 0.4 is ideal** for **efficiency**.
- **Higher Strouhal number** creates significantly **higher thrust** but also adds much more kinetic energy into the surrounding water, **lowering efficiency**.

Future Work

- Modify code to model free-body fish instead of fixed
- Explore control methods (classical PID, model predictive control, reinforcement learning)
- Explore more complex flows (wake of vorticity street)
- Implement egocentric navigation strategy such as in [3]

References

[1] M. J. Lighthill, "Note on the swimming of slender fish," *Journal of Fluid Mechanics*, vol. 9, no. 2, pp. 305–317, 1960. doi:10.1017/S0022112060001110
[2] G. D. Weymouth, "Simulation of a swimming dogfish shark," *The Julia Language*, Aug. 12, 2021. [Online]. Available: https://julialang.org/blog/2021/08/sharks/. [Accessed: Apr. 7, 2025]
[3] D. Fan,L. Yang,Z. Wang,M.S. Triantafyllou,& G.E. Karniadakis, Reinforcement learning for bluff body active flow control in experiments and simulations, *Proc. Natl. Acad. Sci.* U.S.A. 117 (42) 26091-26098, https://doi.org/10.1073/pnas.2004939117 (2020).

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