Hydrodynamics of Undulatory Fish Locomotion

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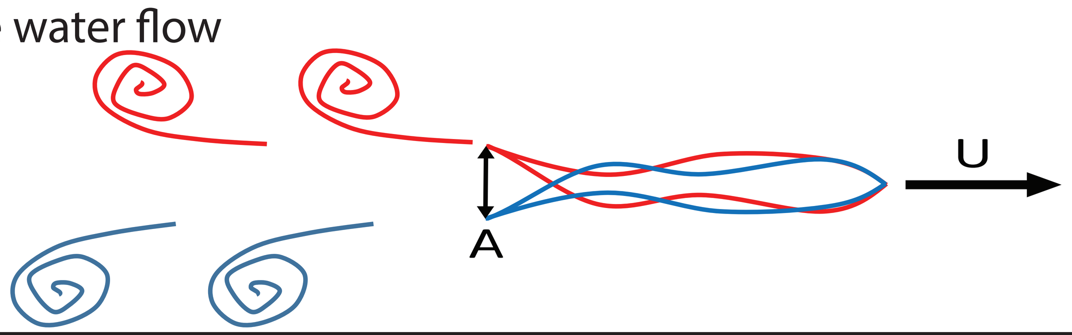
Purpose

By taking inspiration from fish locomotion we can design more efficient mechanical propulsion systems for neutrally buoyant craft such as submarines and airships. Fish utilize their complex musculature to propel themselves through water, but simpler mechanics are possible with our technology. In this study, the hydrodynamics of fish locomotion are modeled using a three-dimensional computational fluid dynamics (CFD) simulation of a thin undulatory plate. The rectangular plate mimics the waveform of carangiform swimming by dividing the model into thirds along the axial flow direction with each section oscillating in a synchronized fashion.

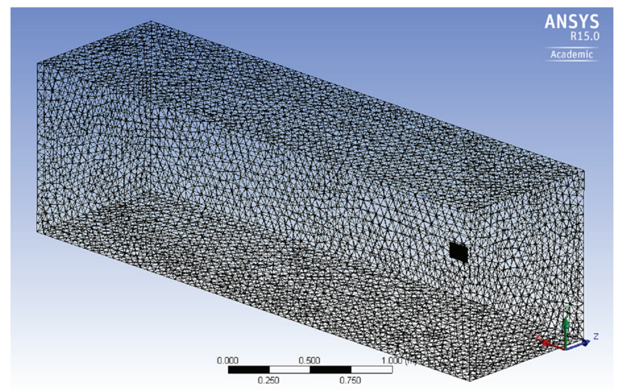
Background

- Fish use their musculature to create a wave motion that travels along the length of their bodies
- The fish push on the water and form vortices that shed at the end of the tail
- The non-dimensional parameter, Strouhal number (St) can be used to characterize the oscillating flow mechanics of fish locomotion
- f is the frequency of vortex shedding, A is the tail tip amplitude, U is the relative speed of the fish to the water flow

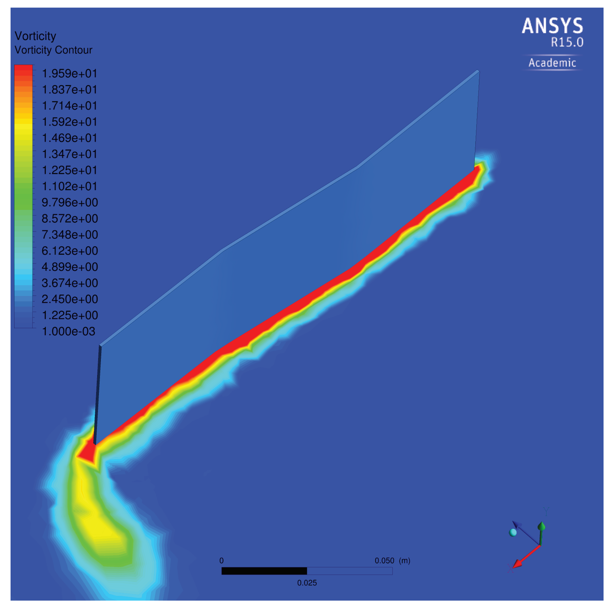
$$St = \frac{fA}{U}$$



Methodology



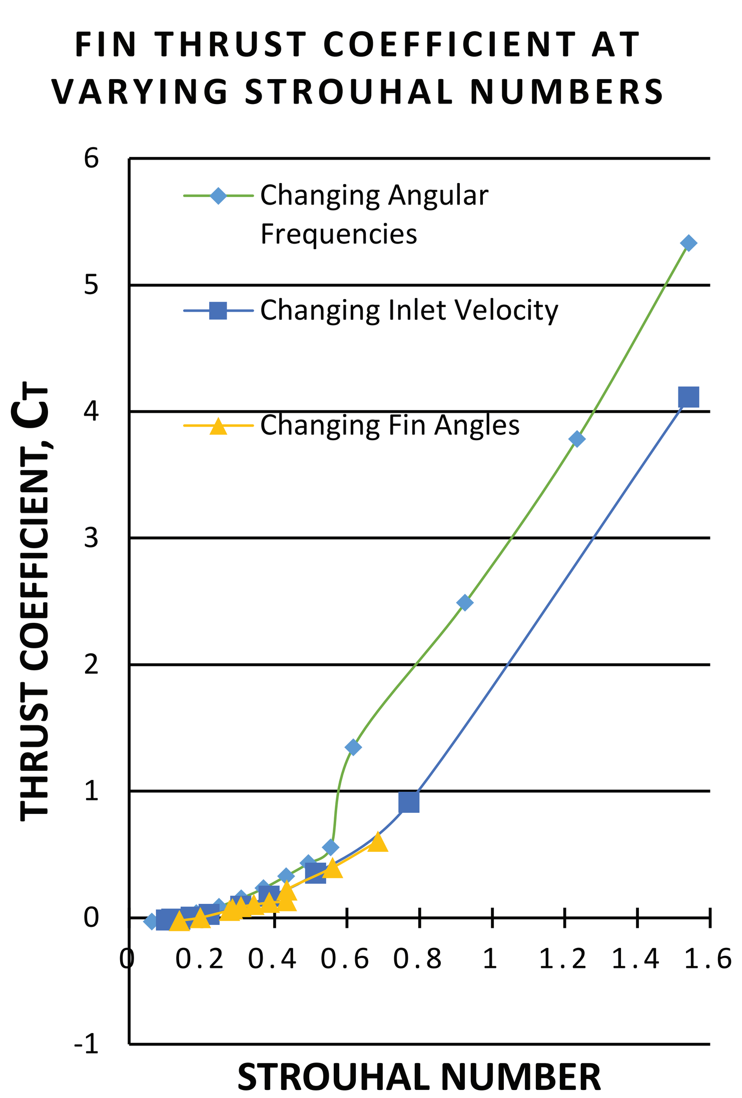
Simulation Mesh Domain

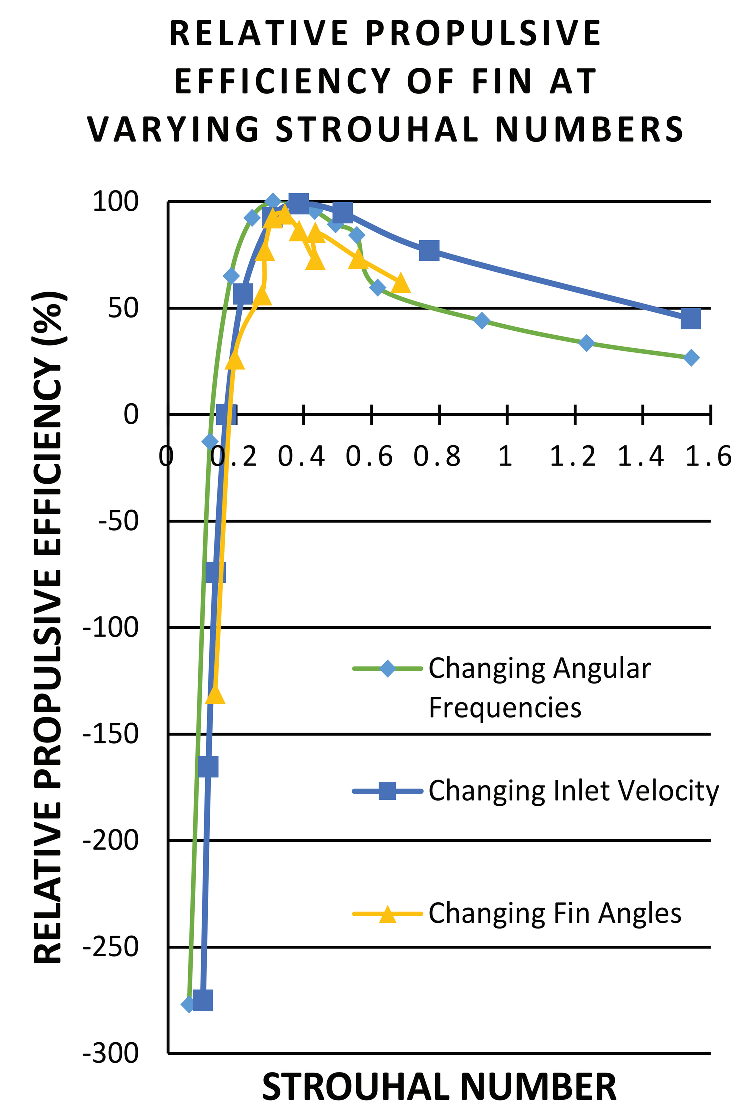


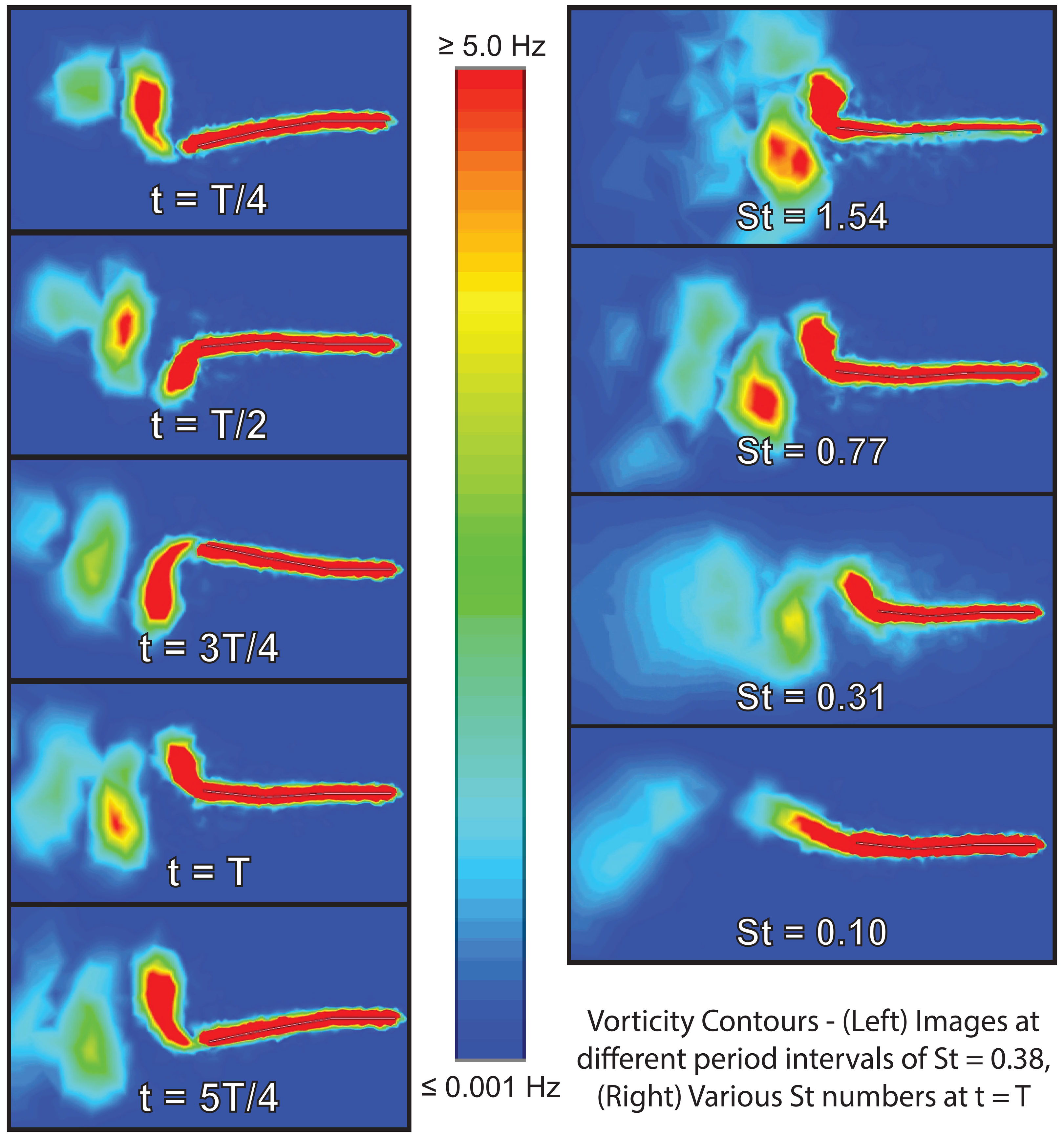
Isotropic View of Fin Model

- Chosen model is a thin flat plate with three sections that move to mimic the undulatory motion of fish
  - The first section is stationary, while the second and third oscillate as sinusoidal functions
- The ANSYS Fluent CFD software solves the Navier-Stokes equations using various numerical methods to calculate the flow properties
- The St can be altered by varying:
  - angular frequency of the fin sections
  - inlet flow velocity
  - the max angles for each section of the fin

Results



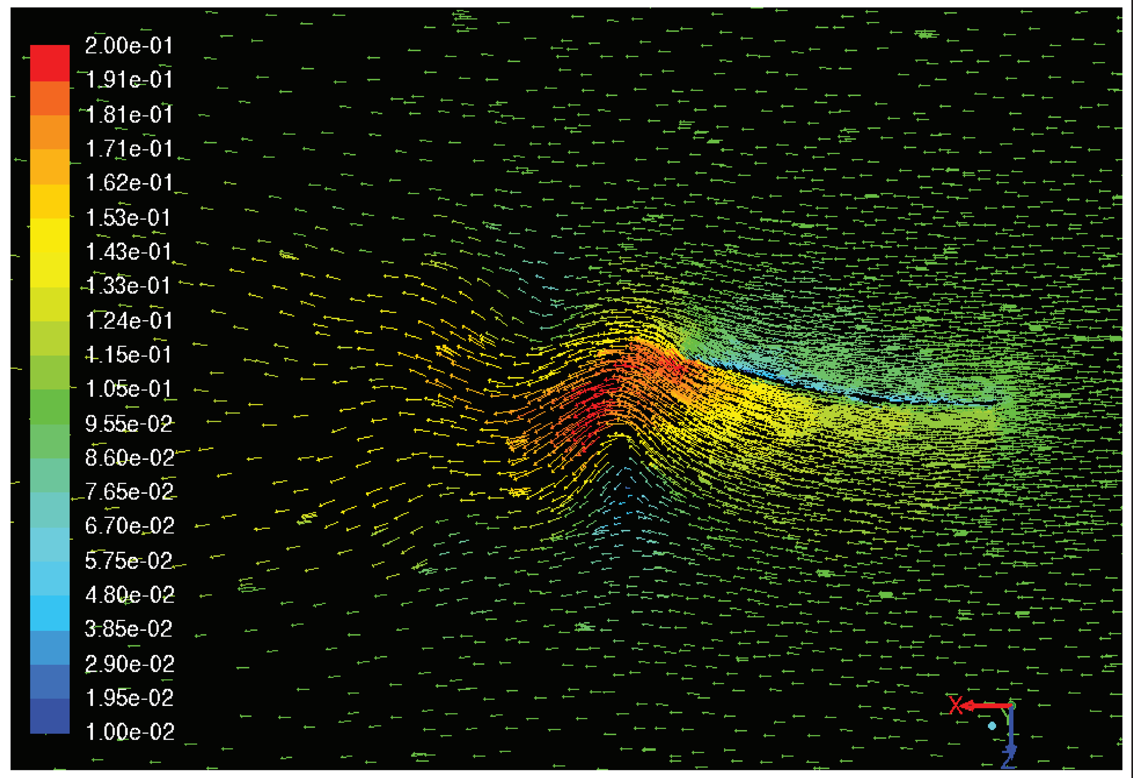




Vorticity Contours - (Left) Images at different period intervals of St = 0.38, (Right) Various St numbers at t = T

Discussion

- The highest efficiencies for the model are within the St range of 0.3 - 0.5
- Increase in St leads to higher thrust production but at the cost of efficiency
- Due to difficulties with the CFD solver the actual values of efficiency are not accurate (peak efficiency being 18%), but the relative efficiencies can still be used qualitatively
- Simulation images show vorticity development at the end of the fin model

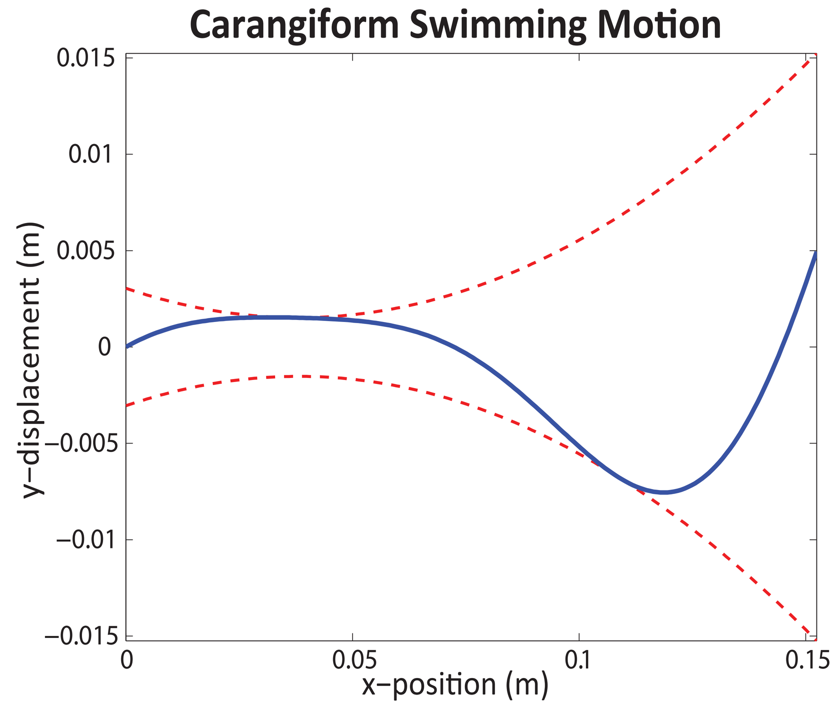


Velcoity vector plot for St = 0.31 at t=3T/4

Conclusions

The fin model in this study is an approximation to carangiform locomtotion, and an important step in developing new propulsion methods. By analyzing the fin model in terms of the non-dimensional Strouhal number, the results can be scaled to different regimes. The roughly calculated efficiencies for this fin model, which peaked at about 18%, are not high enough to compete with propulsion systems currently used in submarines and airships. Improvements in the design of this undulatory mechanical fin to yield higher efficiencies would be a great innovation to expand our reach into both the sea and sky.

Future Work



$$y(x,t) = (a_0+a_1x+a_2x^2)\sin(kx-\omega t)^*$$

- Finding a new method to calculate the work done by the fin model for accurate efficiency calculations
- Running simulations with more variety in section rotation angles
- Testing the fin model in still water (zero inlet velocity)
- Increasing number of divisions along fin model to yield a better approximation of the carangiform locomotion

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*Borazjani, Iman, and Fotis Sotiropoulos. *Numerical Investigation of the Hydrodynamics of Carangiform Swimming in the Transitional and Inertial Flow Regimes*. The Journal of Experimental Biology, May 2008.