The Virtual Aquarium: Simulations of Fish Swimming

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Abstract

Introduction
Fish swimming is an important area of research, with relevant developments on biomechanics, robotics and mathematical modeling. Usually, in fish swimming simulations, fish motion is assigned, and much efforts are put on fluid dynamics [1]. Here, following [2], we simulate muscles contraction by using the notion of distortions (also known as pre-strains), emphasizing the kinematical role of muscle, the generation of movement, rather than the dynamical one, the production of force; within this framework, force arises only when motion is hampered by some sort of constraints. In our case, the lateral motion of the fish is re-acted upon by the force exerted by the surrounding fluid.

A proper undulatory movement of a fish-like body is reproduced by defining a pattern of muscles activation, tuned both in space and in time. We use as reference the book by Videler [3], and we try to reproduce the key features of carangiform swimming. Two-dimensional analyses of fish locomotion have shown that fishes of very different body types such as eels, trout, mackerel, and tuna show very similar patterns of body movements when viewed in a horizontal section during steady undulatory locomotion [4].

Use of COMSOL MULTIPHYSICS
Our approach to simulate fish swimming requires multi-physics, and deeply uses advanced features of COMSOL: non-linear solid mechanics with large distortions to generate fish motion, and fluid mechanics to simulate the Fluid-Solid Interactions (FSI) that makes the fish swim. Moreover, 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.

Fish is modeled as a 2D solid undergoing large displacements, and water is modeled as a fluid. The action of fish muscles is modeled in COMSOL by defining a pre-strains field modulated in both time and space. Skew-symmetric pre-strains with respect to the fish axis yield undulatory movement, and as axis curvature is related to pre-strains, it is possible to achieve a fine control of the lateral displacement of the fish model. Both solid and fluid are modeled using the FSI interface of COMSOL.

Fish motion yields mesh deformation, and fish swimming eventually yields to a so large deformation that the automatic re-meshing feature is needed. BDF (Backward Differentiation

Formula) order is also important as it influences the re-meshing of the model; to reduce spurious oscillations we set maximum BDF order at 1. It is important to note that the fish is not constrained at all, and that its swimming-like behavior is an outcome of our simulations.

Results
The results are compared with empirical general trends of fish locomotion taken from [3]; in particular, we focus on the relationships between fish length, amplitude of the undulatory motion, speed of the contraction wave traveling along the body, and the realized swimming speed. Our findings show satisfactory agreement between the model and actual measurements.

Conclusion
We proved the feasibility of tackling such a complex problem as fish swimming with COMSOL; our results are encouraging, and provide the basis for further development.

Reference

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Figures used in the abstract

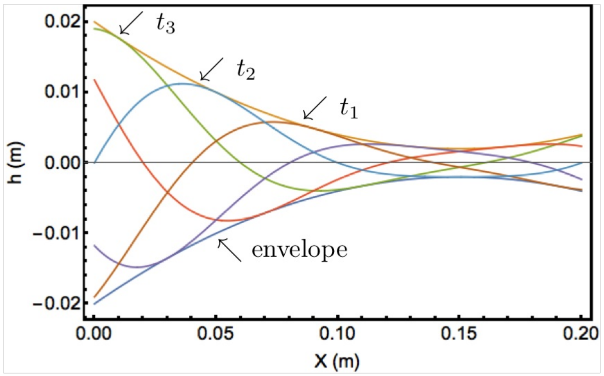

Figure 1: Shape of the fish axis at different times; amplitude of movements is much larger at the tail (left) than at the head (right), and is enclosed in the envelopes. It is present an amplitude wave moving towards the tail, see the position of amplitude maximum at times t1 < t2 < t3; fish motion is rightward.

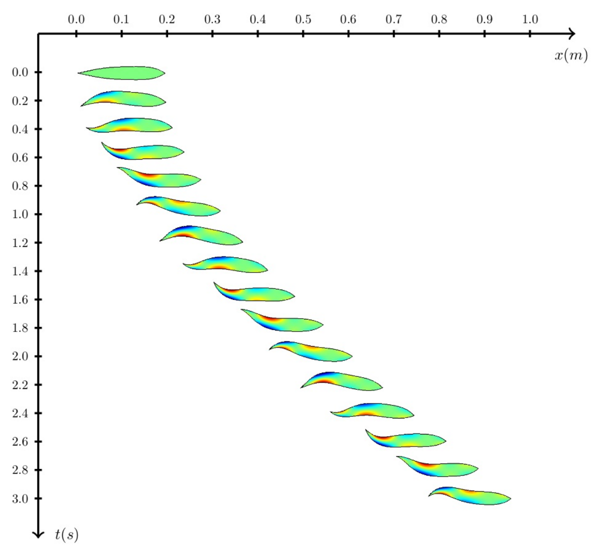

Figure 2: Sequence of shapes assumed by the fish as consequence of muscles activation; color map denotes muscle status: red contracted, blue elongated. This undulatory motion gives the thrust required to swim rightward.

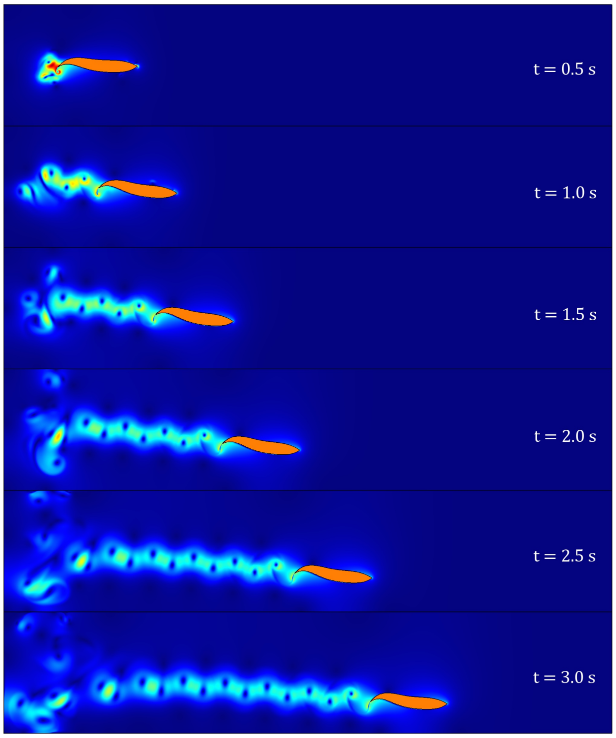

Figure 3: Snapshots of fish swimming; muscles stroke bends the fish and produces swimming thrust. A long wake lies behind the fish. It is worth saying that swimming is realized in the simulation by tuning the muscles contraction pattern in both space and time.

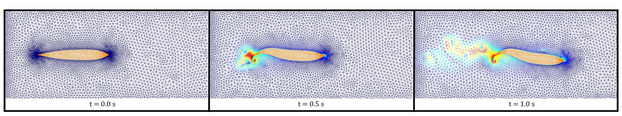

Figure 4: The fish does not have constraints, and swims freely in a large fluid domain; thus, both moving meshes and re-meshing techniques are used to solve the FSI problem. Actually, with moving mesh we deal with the local motion of the fish; with re-meshing, we are able to simulate long distance swimming.