Bio-inspired propulsors for fast and efficient swimming

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Fliers and swimmers found in nature are amazingly adept, demonstrating high degrees of efficiency and maneuverability beyond those of engineered systems. Motivated by our desire to engineer systems of similarly high (and even greater) performance, we seek to understand the underlying physics of high-performance bio-propulsors. This is accomplished through a combined experimental and numerical approach.

We consider a simplified model of fish swimming, namely a sinusoidally pitching and heaving foil in a nominally two-dimensional flow. The theoretical groundwork for the analysis of oscillating foils was laid by Theodorsen (1935) and Garrick (1936), and many studies have since been performed (Wu 2011). Although a robust theory has been developed, it is somewhat intractable and the level of detail mires the physical insights which could be extracted. We show that simple scaling arguments based only on the consideration of forces from quasi-steady lift and unsteady added mass are able to collapse a wide range of experimental data. The simplicity of the scaling arguments allows for easy physical insights.

Building in complexity, we investigate the propulsive performance of different (i.e. non-sinusoidal) swimming gaits. The effectiveness of non-sinusoidal gaits is scantily reported in the literature, although some studies have hinted at improved performance (Koochesfahani 1989, Read et al. 2003). We consider gaits described by Jacobi elliptic functions, since these functions allow us to vary the motion from triangle-like to sinusoidal to square-like by only varying one parameter. Again, we are able to collapse the experimental data based on simple scaling arguments, and particle image velocimetry (PIV) elucidates the wake physics.

We report the progress made on adjoint-based numerical optimization to be used to investigate the effectiveness of different swimming gaits. The adjoint formulation of a two-dimensional immersed boundary method (Taira & Colonius 2007, Colonius & Taira 2008) is used to efficiently calculate the gradient of a desired cost functional with respect to many parameters. This allows us to efficiently optimize the swimming gait over a very large parameter space, and also provides sensitivity information with respect to the different parameters, further elucidating the physics. We present results for a problem structurally similar to the Navier-Stokes problem, and detail the progress made for the full problem.

Further building in complexity, we consider a fully three-dimensional flow in which we investigate the effects of planform shape on propulsive performance. The differences in propulsive performance are explained by analysing the three-dimensional wake; this wake is visualized by stacking several slices of planar PIV to form a volume.

Finally, future directions are discussed. Foremost among these are experimental optimization, numerical optimization, energetic and stability analysis of the wake, and plans for a novel cyber-physical experimental facility.
References


