NUMERICAL SIMULATIONS OF UNDULATORY SWIMMING AT MODERATE REYNOLDS NUMBER

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The undulatory mode of locomotion predominates in aquatic organisms over an enormous range of Reynolds numbers, from the flagellar propulsion of spermatozoa, to the carangiform mechanics of vertebrate fish and aquatic mammals. An ostensible reason for the prevalence of this mode is its effectiveness when either resistive (viscous) or reactive (inertial) forces are used in the lateral pushes to achieve forward motion. Less well understood are the interactive roles of viscous and inertial forces in moderate Reynolds number locomotion. Lighthill [3] hypothesized that the thrust-producing mechanism is primarily reactive, and based his elongated body theory on the inertial force produced by the added mass. Viscosity was deemed important only as a contributor to drag, which was estimated from limp fish. A recent investigation of inviscid swimming by Kanso et al. [2] has clearly shown the potential for net displacement with reliance on inertial forces alone. Using particle image velocimetry of swimming fish, Wolfgang et al. [4] revealed that vortical structures shed over the length of the body may be actively manipulated to improve the swimming efficiency. Therefore, more work is necessary to clarify the role of vorticity, in order to exploit it in biomimetic technology.

In this work, numerical simulations conducted with the viscous vortex particle method [1] are used to elucidate the fluid dynamics of a simple model for undulatory locomotion, a two-dimensional system of three linked ellipses. The high-fidelity method solves the incompressible Navier–Stokes equations by focusing on the creation, diffusion and convection of vorticity via the use of computational particles. A recent extension of the method to dynamically coupled problems, in which the motion of the body is simultaneously solved for with the motion of the fluid, allows the exploration of free swimming. Thus, while the angles between the links are prescribed, the evolution of the position and orientation of the system is determined during the course of the simulation.

Results for several Reynolds numbers will be presented and compared with the inviscid limit of Kanso et al. [2]. It is found that viscosity in this system has a negative role, and that progressive increases in Reynolds number lead to monotonic increases in forward swimming speed that approach the inviscid limit. The energy expenditure and efficiency of the motion will be discussed. In addition, a variety of undulatory kinematics—to the extent allowed in the simple three-linkage model—will be explored. The potential for obtaining reduced-order models of this motion will also be discussed.

References

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