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Modelling the hydrodynamics of swimming fish, from individuals to infinite schools

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DISCUSSION

The preceding chapters describe the most important results of the work done for my doctoral thesis. Chapters 2, 3 and 4 each describe a more advanced version of the computer model and its application to a more complex situation, from static shapes in flow (Chapter 2) to infinite schools of undulating fish (Chapter 4).

The swimming of fish has in the last fifteen years been studied in a variety of computer simulations of hydrodynamics, often with interesting results (Liu et al., 1996; Wolfgang et al., 1999; Kern and Koumoutsakos, 2006; Sui et al., 2007; Borazjani and Sotiropoulos, 2008). Our simulation method is a valuable addition to this field for two main reasons: First, its lack of a spatial grid makes it ideally suited for the study of organisms, especially those that change their shape and relative position. Second, it is extremely fast, without sacrificing hydrodynamical accuracy. All simulations in this thesis were carried out on a single, ordinary desktop PC or laptop, and even the largest simulations took less than a week. It should be noted however that this speed comes at the cost of stochastic noise. The influence of this noise decreases as the system under study becomes larger. This means that the model is most suitable for either high Reynolds numbers, (above 1000) where the noise is largely cancelled out through the law of averages, or extremely low ones (below 1) where Brownian motion is relevant.

Our finding in Chapter 2 that the addition of trailing, tail-like plates to cylinders increases their drag coefficient at low Reynolds numbers, but decreases drag at higher ones, suggests that tails which are flat orthogonally to the direction of undulation are more useful for larger organisms, such as the fish that we study in the subsequent chapters. Further, we argue that the *effective* Reynolds number of a two-dimensional object is higher than that of the corresponding three-dimensional one. In two dimensions the degrees of freedom are reduced and there is no third dimension for energy to dissipate into. This causes all flow phenomena such as the onset of vortex shedding and turbulence to occur at a much lower Reynolds numbers in 2D than in 3D (Table 2.3). We use this finding in Chapters 3 and 4 to explain why our simulations of fish shapes with Reynolds numbers of approximately 1200 are reasonable approximations of real fish swimming at much higher Reynolds numbers (to the order of 10000).

In Chapter 3 we test the effects of the common practice in computer simulations to constrain swimming fish from accelerating. We find that constraining longitudinal acceleration has no effect, but constraining lateral acceleration increase the force which the fish exerts, causing its speed speed and patterns of hydrodynamical forces and flow to resemble those of unconstrained fish with a higher tailbeat frequency. Because constraining the acceleration of individuals had no qualitative effect for single fish in Chapter 3, we expect that our choice in Chapter 4 to keep the relative positions of individuals in the schools fixed will also not qualitatively affect the patterns of force and efficiency.

The most notable result of our simulations of groups of fish is that the efficiency of the vast majority of spatial configurations and spacings was higher than that of a single fish. This suggests that travelling in groups is likely to save energy for some of its members in many more cases than was originally thought.

Our simulation results are consistent with three findings from our meta-analysis of data of real fish (Chapters 3, 5). Firstly, swimming speed increases linearly with tailbeat frequency as well as with the speed V of the propulsive body wave. Second, the slip ratio U/V at low to intermediate Reynolds number (1000–10000) is strongly dependent on the Reynolds number. Third, rather than there being a single optimal Strouhal number at which fish swim (Triantafyllou et al., 1993), the Strouhal number changes with the Reynolds number. Our simulations of single fish only experimented with different tailbeat frequencies. For a more thorough comparison between simulations and data of real fish it would be necessary to change also parameters such as fish size, tailbeat amplitude and the wavelength of the undulation. This could be used to further validate the model against experimental data. Also of interest would be to study a different body shape and swimming style such as those of an eel against simulations and empirical data (Borazjani and Sotiropoulos (2009); Gillis (1998); Müller et al. (2001), Chapter 5).

Besides further comparison to empirical data, there is of course much work still to be done to improve our understanding of the hydrodynamics of swimming fish, especially in schools. On current hardware it will be possible to study larger groups in our model. This allows for finite school sizes, with individuals that undulate out of phase and with different tailbeat frequencies. The individuals could also be made to swim more naturally, by making their bodies undulate in response to the flows, as well as making them sense flows and dynamically adjust their undulation to optimally exploit them, for example by using the Kármán gait (Liao et al., 2003b). Social responses, such as the commonly-used simulation rules of avoidance, alignment and attraction (Hemelrijk and Kunz, 2005; Hemelrijk and Hildenbrandt, 2008; Hemelrijk et al., 2010) could also be added to create schooling behaviour that is more natural. Or course, for this individuals must be able to move and change their relative positions freely unlike the rigid lattices we studied (Chapter 4). To this end, a control system could be added to the fish so that they curve their body to make turns and change their tailbeat frequency to navigate change their velocity, as has been shown to work in robotic fish (Shao et al., 2008).

The work presented in this thesis has answered several important questions about undulatory swimming and its study in simulations, for example the effects of constraining individuals' acceleration, and the hydrodynamical benefits of travelling in groups. Just as many, if not more, questions remain however. Fortunately, this thesis has also resulted in a simulation tool that will allow many of those questions to be answered in future projects.