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

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SUMMARY

This thesis investigates the hydrodynamics of fish that swim by steady undulation of their body. This is done by means of a computer model (specifically the Multiparticle Collision Dynamics method) and of a meta-analysis of published experimental data.

In the computer model, the water and its dynamics are simulated by means of millions of particles that move and collide. From this behaviour at the micro-scale, correct hydrodynamics emerge at the macro-scale. From studying static shapes in flow in a channel we find that when attaching long tail-like plates, drag increases at low Reynolds numbers but decreases at higher ones, suggesting that tails are only useful for larger organisms. Further, we examine the hydrodynamics of single shapes that change their position, orientation and form: a flapping insect wing (for validation purposes) and an undulating fish. The results of both cases agree with experimental data. We show that the commonly used practice in simulations of fish swimming to constrain the fish from accelerating can influence results. We find no effect of constraint of acceleration in the longitudinal direction. On the other hand, constraint in the lateral direction increases the swimming speed and exaggerates patterns of force and flow, so that they resemble those of unconstrained fish with higher tailbeat frequencies. Our third study concerns infinite schools of fish in several different spatial configurations in the model. We investigate the diamond-shaped lattice that is theoretically optimal and a rectangular lattice. Further, to separate out the effects of longitudinal and lateral neighbours we simulate an infinitely long progression, or 'line' and an infinitely wide 'phalanx'. Our results confirm theoretical predictions that having lateral neighbours is beneficial for efficiency, and that a closely-spaced diamond lattice causes individuals to encounter a low-velocity area ahead of them. Unexpectedly however, the prediction that this pattern of the closely-packed diamond lattice increases efficiency is not borne out by our results. Remarkably we also show that in most cases swimming directly behind a fish in its undisturbed wake is beneficial as regards speed and efficiency.

We extend the insights gained from our simulations by means of a meta-analysis of the scientific literature on steady swimming of real fish. The size of our data set leads to several significant insights that apply across species. Most importantly, we show that the strongest predictor of swimming speed U is the speed V of the rearwards-traveling body wave. Further insights include the fact that the slip ratio U/V is a function of the Reynolds number (which is also the case in our model).

In conclusion, this thesis increases the understanding of steady, undulatory swimming, both alone and in groups.