Phase locking and pattern formation in tandem fish swimming

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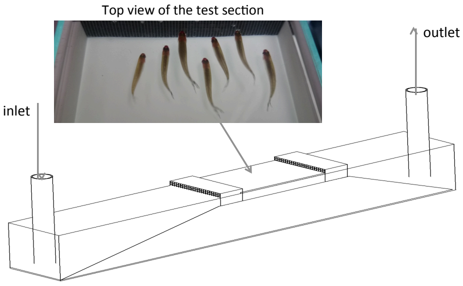
In this work, we address the case of red nose tetra fish *Hemigrammus bleheri* swimming in groups in an uniform flow, giving a special attention to the side by side configuration of different individuals within a chosen population. We bring evidence of a synchronization for the case of two fish, where the swimming modes are dominated by "out of phase" and "in phase" configurations and the statistics depend on the swimming speed (imposed in the present experiment by the flow rate in the swimming channel). We conjecture that the transition to this synchronization state is correlated with the magnitude of the hydrodynamic pressure generated by the fish body during each swimming cycle (see [2]) . From a careful analysis of the spatiotemporal patterns corresponding to those synchronized modes for a fish pair, we give new insights on the spatial configuration of cooperative swimming of fish [1], based both on energy saving and efficient information transfer.

Experimental setup

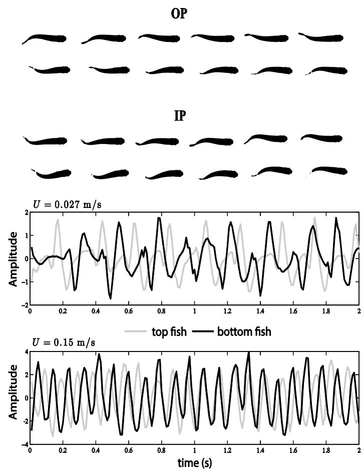
The experimental setup consists of a closed-loop water channel with a test section of 19 cm in the stream-wise direction, 11 cm width and 2.2 cm height. The shallow height of test section was chosen to minimize out of plane swimming of different fish. The image acquisition was carried out at 100 Hz, which was enough to time-resolve the tail beating dynamics. An in-house tracking code was developed using Matlab to extract ther 2D kinematics of the fish midline.



Synchronisation

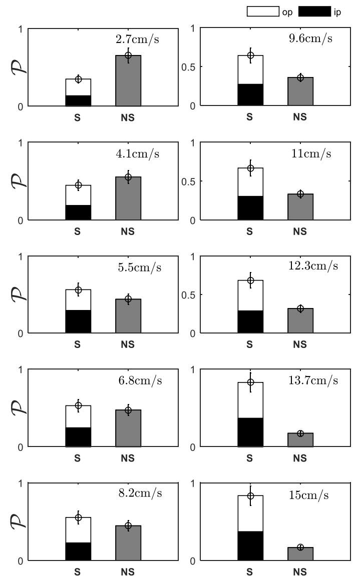
Two different modes of synchronized behavior are observed. In-phase mode (IP) or out of phase mode (OP). The statistics of the synchronization is obtained by counting the flapping cycles spent in-phase and out of phase throughout an experiment.

The time series show two typical tail tip kinematics for slow (2.7 cm/s) and fast (15 cm/s) swimming velocities for a pair of fish. As can be seen, only the high swimming speed gives rise to synchronization.

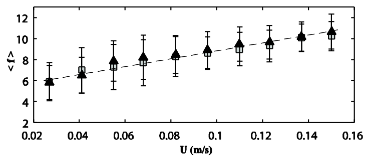


Phase locking

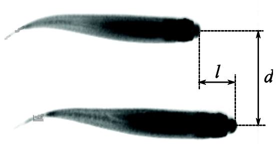
The cumulated statistics (averaged over seven different pairs of fish) of the synchronized states as a function of the swimming velocity show that: For relatively slow swimming velocity, the fish spend most of the time swimming in a non-synchronized state (NS). This tendency changes with the swimming velocity where more and more synchronisation states (S) are observed in the distribution. The transition from independent to collective swimming is here clearly based on fish gate. Also the OP and IP are comparable to each other, but at higher swimming velocity OP dominates IP

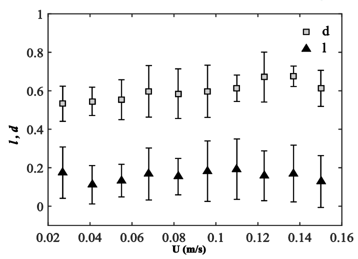


Averaged tail beating frequency for both top and bottom fish vary linearly with the swimming velocity U. It can be also observed that the mere observation of frequency locking in tandem swimming is not enough criteria to describe synchronization.



Pattern formation





The two characteristic lengths *l* and *d*, are observed to be constant over a large range of swimming speeds. Fish seem to choose a stable configuration independent of their gait.

- **The distance *d*, which can refereed to as the distance to nearest neighbor is found to be around 0. 5 - 0.6 of fish body length.**
- **The distance *l*, found to be around 0. 1 - 0.2 of fish body length.**

References

[1] Weihs, D (1973) Hydromechanics of fish schooling. Nature, 241: 290-291.

[2] Faucher K, Parmentier E, Becco C, Vandewalle N, Vandewalle P (2010) Fish lateral system is required for accurate control of shoaling behaviour. Animal Behaviour, 79: 679–687.

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