Vortex interactions during in-line swimming in live fish: Implications for fish schooling

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1 Introduction

Schooling in fish has long been hypothesized to provide hydrodynamic advantages. Most notably, Weihs (1973) [1] predicted that swimming in a diamond formation allows fish to exploit the reduced velocity (drag) wakes shed by pairs of upstream fish. Studies have since shown the energetic benefits of swimming in drag wakes [2]. However, new evidence suggests that these reduced velocity wakes are not the only hydrodynamically beneficial regions. Computational simulations [3], flapping foil studies [4] as well as robotic studies [5] have indicated that in-line swimming in thrust wakes could provide similar benefits, even though these regions are characterized by higher mean flows than the free stream. Given this evidence, it remains yet to be shown how live fish perform in such thrust wakes. Here we present a controlled experiment in which we used a mechanical flapping foil and exposed trout to artificially generated fish-like thrust wakes while capturing both fish kinematics and flow interactions. Our preliminary results indicate that trout exploit the vortex structures in thrust wakes.

2 Methods

We used brook trout (*Salvelinus fontinalis*, 13-19 cm body length, n=8) for our experiments and swam them in a flow tank with a swimming space of 28 cm x 28 cm x 54 cm. We tested these fish under two conditions: 1) In an artificially generated thrust wake and 2) in free-stream flow. The nominal flow speed was set to 0.3 m/s in both conditions.

2.1 Artificial thrust wake

We implemented the artificial thrust wake using an actuated two degree of freedom (DOF) rigid flapping foil, which emulates the tail fin portion of a swimming fish. The two DOFs include a sway (lateral side-to-side) as well as a yaw (rotating) movement and were parametrized as follows:

$$y_{sway} = a_{sway} \sin(2\pi f t), \quad (1)$$

$$\phi_{yaw} = a_{yaw} \sin(2\pi f t - \frac{\pi}{2}), \quad (2)$$

where a_{sway} and a_{yaw} describe the sway and yaw amplitudes, respectively. f indicates the frequency and t the time in seconds. The generated thrust wake shows the following main features of a fish-like wake: Using particle image velocimetry (PIV) we confirmed that vortices with alternating orientation are shed at the tip of the foil at the instances of maximum lateral excursion and form a reverse Kármán vortex street as observed in free swimming fish [6]. The Strouhal number St ($St = \frac{fA}{U}$, tail-beat frequency f, maximum tail-beat excursion A, forward speed U) can be interpreted as the ratio of sideways to forward movement, and falls typically in the range of $0.2 < St < 0.4$ for fish [7]. We chose our flapping foil parameters accordingly and achieved a Strouhal number of $St = 0.267$ ($f = 2$ Hz, $A = 0.04$ m, $U = 0.3$ m/s). The corresponding flapping foil amplitude A was achieved by setting $a_{sway} = 1$ cm and $a_{yaw} = 20°$. Finally, we found a 5 % increase of the average flow speed in the thrust wake compared to the free stream, confirming another important characteristic of a fish-like thrust wake.

2.2 Quantification of kinematics and flow patterns

In order to visualize flow dynamics around trout under freely swimming and thrust wake conditions we carried out PIV [8]. For this purpose, we seeded the water with near-neutrally buoyant plastic particles ($\sim 50\,\mu$m mean diameter) that were illuminated by a laser light sheet through the middle of the fish body. We then recorded from a ventral view by means of a high-speed camera at 1000 frames per second, simultaneously capturing the flapping foil, the swimming fish and the illuminated particles. We also used a side-view camera to confirm that individuals were swimming in the middle of the laser sheet.

The high-speed videos were subsequently processed in a custom script in MATLAB to mask the fish body. We then computed the fluid velocity fields using DaVis 8.3 (LaVision Inc.). We further extracted both tail-beat frequencies and midline kinematics from the videos.

3 Preliminary results

Our initial experiments show that trout actively chose to swim in the increased flow speed region of the thrust wake and we observed this behavior in 8 individuals. Furthermore, we found that fish adapted their tail-beat frequency to match it with the vortex shedding frequency of the flap-

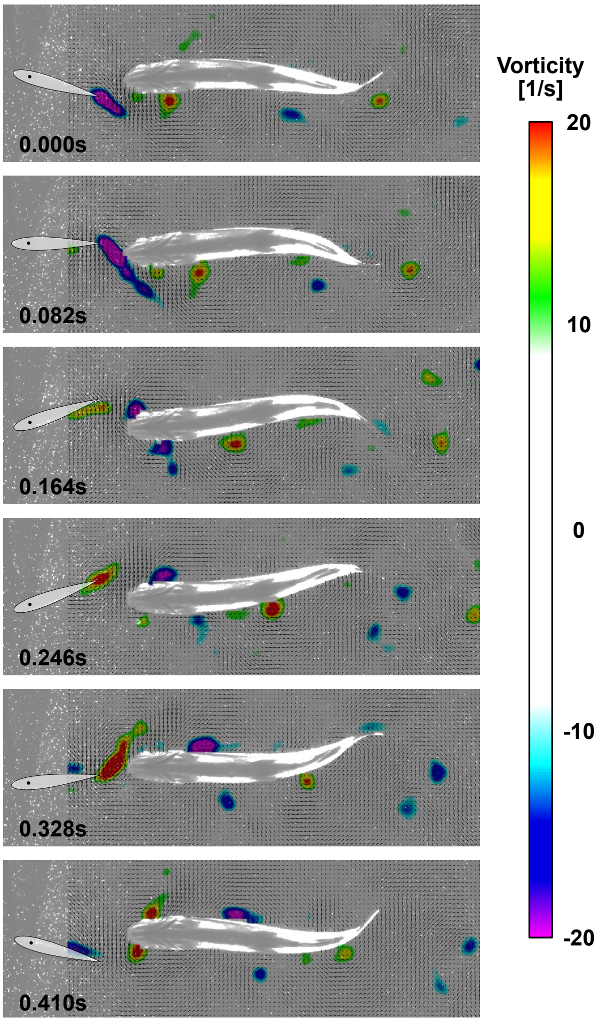

Figure 1: Velocity field and visualization of vorticity: Trout swimming behind a flapping foil intercept vortices. Parts of these vortex structures stay attached and travel along the body.

ping foil. In a few specific cases of smaller size fish that swam at higher frequencies for the given free-stream flow speed, we observed significantly reduced tail-beat frequencies when swimming behind the flapping foil at the same speed. This indicates that these fish were able to save energy under these conditions because tail-beat frequency is strongly linked to metabolic rates for similar tail-beat amplitudes [9].

Flow visualization from our PIV data (Figure 1) further indicates that fish are interacting with the oncoming vortices shed from the foil and as a result they change the structure of the flow in the thrust wake. In many cases trout positioned themselves closely behind the flapping foil and intercepted the oncoming vortices. We also observed that by angling their anterior body with respect to the oncoming flow, vortices stayed attached and travelled along their body.

4 Discussion and future steps

Previous computational work suggests that undulatory swimmers in a thrust wake can achieve increased thrust production by exploiting leading-edge suction in a wavy wake [10]. Given that vortices are low-pressure regions in the flow and that trout in our experiments actively intercept vortices, our preliminary results indicate that live fish are exploiting this very same effect of leading-edge suction. In a next step we plan to computationally derive the overall pressure field [11] around the swimming trout in the thrust wake to confirm this hypothesis and to further understand if and how attached vortices contribute to forward thrust production.

Our preliminary results as presented here in a controlled experiment with live fish confirm the hydrodynamic advantages of swimming in thrust wakes. This provides, in addition to drag wakes, another potentially beneficial swimming region to save energy in fish schools and suggests that there are a variety of locally optimal swimming positions.

References

[1] D. Weihs. Hydromechanics of Fish Schooling. *Nature*, 241(5387):290, 1973.

[2] J. C. Liao, D. N. Beal, G. V. Lauder, and M. S. Triantafyllou. The Kármán gait: novel body kinematics of rainbow trout swimming in a vortex street. *Journal of experimental biology*, 206(6):1059–1073, 2003.

[3] I. Akhtar, R. Mittal, G. V. Lauder, and E. Drucker. Hydrodynamics of a biologically inspired tandem flapping foil configuration. *Theoretical and Computational Fluid Dynamics*, 21(3):155–170, 2007.

[4] J. W. Newbolt, J. Zhang, and L. Ristroph. Flow interactions between uncoordinated flapping swimmers give rise to group cohesion. *Proceedings of the National Academy of Sciences*, 116(7):2419–2424, 2019.

[5] L. Li, M. Nagy, J. M. Graving, J. Bak-Coleman, G. Xie, and I. D. Couzin. Vortex phase matching as a strategy for schooling in robots and in fish. *Nature Communications*, 11(1):5408, 2020.

[6] M. S. Triantafyllou and G. S. Triantafyllou. An efficient swimming machine. *Scientific american*, 272(3):64–71, 1995.

[7] M. Saadat, F. E. Fish, A. G. Domel, V. Di Santo, G. V. Lauder, and H. Haj-Hariri. On the rules for aquatic locomotion. *Physical Review Fluids*, 2(8):083102, 2017.

[8] E. G. Drucker and G. V. Lauder. Locomotor forces on a swimming fish: three-dimensional vortex wake dynamics quantified using digital particle image velocimetry. *Journal of Experimental Biology*, 202(18):2393–2412, 1999.

[9] J. Herskin and J. F. Steffensen. Energy savings in sea bass swimming in a school: measurements of tail beat frequency and oxygen consumption at different swimming speeds. *Journal of Fish Biology*, 53(2):366–376, 1998.

[10] M. Saadat, F. Berlinger, A. Sheshmani, R. Nagpal, G. V. Lauder, and H. Haj-Hariri. Hydrodynamic advantages of in-line schooling. *Bioinspiration & Biomimetics*, 2021.

[11] J. O. Dabiri, S. Bose, B. J. Gemmell, S. P. Colin, and J. H. Costello. An algorithm to estimate unsteady and quasi-steady pressure fields from velocity field measurements. *Journal of Experimental Biology*, 217:331–336, 2014.