The effect of the wake symmetry in biomimetic propulsion

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The goal of the present research is to quantify, for real self-propelled moving objects, how thrust production can be affected by the wake characteristics (i.e. spatial ordering, mixing rate) while the momentum available for thrust production is kept constant. The main idea is to extract optimal design strategies from the locomotive mechanisms developed by nature in order to transpose them to technological applications. Indeed, we show that controlling mixing in the near wake can increase significantly thrust production for a given momentum input, a result that can be valuable in the design and optimization of artificial biomimetic propellers.

The experiment was performed in a free–surface water tank (900 mm x 800 mm x 500 mm) where an artificial swimmer is submerged. Self–propulsion is achieved by the pitching motion of two rigid foils. The foils are separated by a distance d; the chord (c), maximum width (D) and span (l) have 23 mm, 5 mm and 100 mm in length, respectively. The angular position of each flap is controlled by a small stepper and an adequate driving curve. The set was placed in a cart hanging from a straight rail, allowing it to glide along the longitudinal direction. In order to minimize the friction, an air bearing was used (See Figure 1). We considered two different flapping configurations for self-propelled swimming, which we have named, symmetrical (S) and asymmetrical (A) after the kind of pattern of the resulting wake (See Figure 2.a).

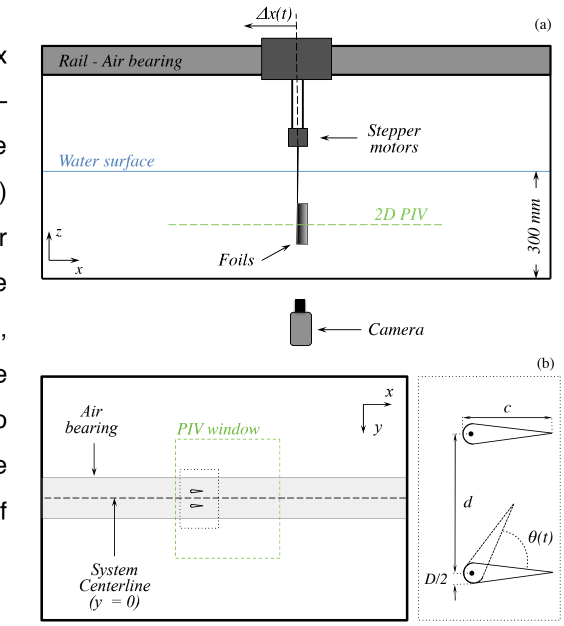

Fig. 1: the experimental device. (a) Side view. (b) The camera view showing details on the foil configuration and the definition of the geometrical parameters.

The measurements. The propulsive force was recovered from the swimmer displacement measurements, such as those presented in Fig.2(b). The following dynamical model was proposed to describe the measurements.

$$m\ddot{x} + \gamma \dot{x}^2 = F_p^{S,A}$$

Where m is the total mass of the swimmer, γx^2 is the nonlinear hydrodynamic drag term and $F_{S,A}$ is the effective propulsive force. To estimate the propulsive force, measurements were fitted using:

$$x(t) = \frac{m}{\gamma} \log \left[\cosh \frac{\sqrt{\gamma F_p^{S,A}}}{m} t \right]$$

Fast 2D PIV measurements were conducted on a fixed observation window to obtain the velocity field. The air bearing setup was blocked on a fixed position for this purpose. Mean flow velocities and fluctuations were extracted from them. PIV measurements were performed over a 25 cm × 20 cm window placed at mid-span of the foils, during 10 seconds at 150 Hz. Polyethylene particles of 10 µm in diameter were used for seeding. Standard particle/laser sheet visualizations were made using 50 µm in diameter, polyethylene seeding particles.

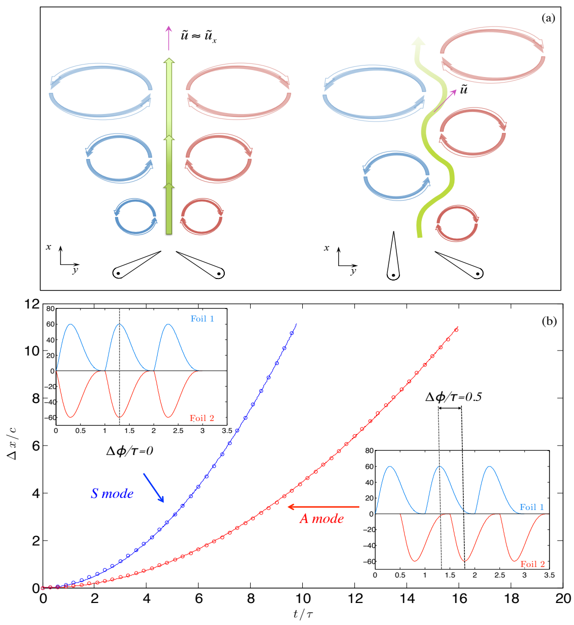

Fig. 2: (a) Simplified schemes of topology and velocity fluctuations of the considered wakes. (b) Example of the swimmer's reduced displacement (Δx/c) on both flapping configurations. Driving curves are correspondingly shown; all profiles are essentially the same, the phase lag (Δϕ) being the only difference.

Results show that after a clear transitory, the swimmer reaches constant velocity. While the symmetric mode proved to be the fastest for a short axis separation, no significant difference between both configurations was detected on the swimming performance if the flaps are separated enough. A similar observation can be made on thrust achievement. As long as the flaps are not placed too close to each other, the performance of both flapping modes as thrust generators is approximately the same. However, when the flaps separation distance is short enough, the symmetric mode has proved to generate higher thrust than the asymmetric one. The higher is the flapping frequency, the greater is the performance difference. Propulsive forces up to 200 and 60 mN were measured for the symmetric and the asymmetric configuration, respectively (See Fig. 3).

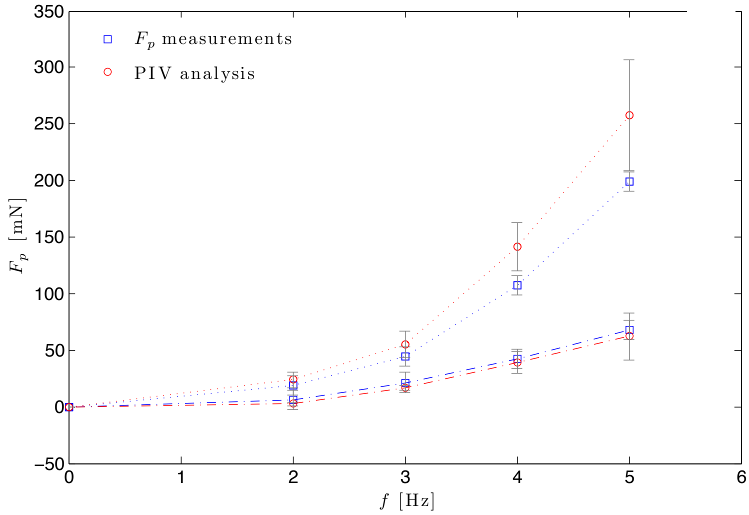

Fig. 3: In blue, propulsion achieved by both kinds of propellers, plotted together as a function of f, setting d/c = 1.7. Dashed-dot lines correspond to measurements made in the asymmetrical configuration; dotted lines indicate the symmetrical mode. The corresponding calculations are presented in red. Error bars were calculated as the standard deviation of values obtained after varying the position of the downstream boundary of the control volume within the region where viscous dissipation and/or 3D effects are negligible.

The propulsive reaction force experienced by the swimmer can be deduced from a classic momentum balance on a given control volume, from mean flow velocities and the mean pressure field, directly recovered or calculated from PIV measurements, respectively. Calculations were made within the context of the turbulent boundary layer approximation for developing jets, considering time-averaged Navier-Stokes equations and the Reynolds decomposition for the velocity and pressure fields for an inviscid incompressible 2D-fluid of uniform density ρ. It can be seen that the asymmetric mode generates much more mixing than its symmetric counterpart and that -as a consequence- the near-wake pressure is significantly lower, modifying the amount of momentum available for propulsion. For each explored experimental condition, F_p can be evaluated from the corresponding velocity and pressure fields; and be compared with direct measurements (See Fig. 3). Both quantities are very consistent in order of magnitude and general behavior with respect to the flapping frequency, which validates PIV measurements to estimate the force in the 2D approximation, but also strengthen the conjectures made on pressure.

Conclusions. Thus, we have shown that the way wakes are generated from the same momentum input has a noticeable effect on the swimming (or flying) performance of self-propelled objects. This dependence is mainly due to a pressure effect that is related to the mixing in the near wake, understood here as the intensity of the fluctuations.

On the other hand, our measurements confirm that some wake configurations have the ability to minimize mixing (here, for the symmetric mode for instance) and save useful momentum. Animals are firstly constrained by their morphologies and needs, and some of them might spend more energy for the same work than others. However, one strategy of optimization for possible human made swimmers or flyers is therefore to control fluctuations in the wake by setting properly the time dependent momentum inputs to save energy.