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Propulsive performance of a pair of pitching foils in staggered configurations

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A R T I C L E I N F O

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The propulsive performance and the wake interactions between a pair of pitching foils in several staggered configurations are studied experimentally. Results are limited to cases with in-phase and out-of-phase kinematics. Measurements include thrust forces, input torques and the quantification of the flow field around the flapping system.

The side-by-side configurations have been found to be beneficial in terms of efficiency when compared to the case of solitary foils. If one of the foils is staggered, efficiency is decreased because of the existence of wake asymmetry.

1. Introduction

The study of the complex interactions that take place in fish schools have received considerable amount of attention in the last decades. The overall shape of the schools and the relative position of each individual in them, are characteristic of different species and of the purpose of the school (Camazine, 2003). Collective locomotion reduces the risk of being captured as a prey (Partridge, 1982) and foraging is improved when in large groups of individuals (Pitcher et al., 1982).

From a mechanistic point of view, it seems natural to think that the search for enhanced efficiencies could be driving the formation of fish schools, apart from all other behavioural reasons. Recent developments in the field of underwater vehicles are one of the driving forces for this type of research, not only from the point of view of the interactions between individuals in formations, but because of the possibility of new propellers consisting of pairs or other formations of flapping foils that could be devised in the future.

The changes in performance experienced when swimming in perturbed flows have been studied by Liao et al. (2003b, a) and Liao (2007), in configurations in which the fish is immersed in the wake of a bluff body. Fish can reduce muscle activity when seeing an incoming wake, in fact, Beal et al. (2006) showed how a dead fish experienced thrust when placed in the wake of a bluff body. The theoretical work by Weihs (1973) suggests that the diamond formation in a two-dimensional school of fish swimming synchronously has energetic advantages, when compared to the case of solitary swimming. Therefore, in a infinite periodic arrangement, a fish swimming centred behind two other fish would have and increased efficiency. A possible explanation for this increased performance has to do with the fact that the downstream fish is confined between two incoming wakes, experiencing a similar effect to that in ground effect (Fernández-Prats et al., 2015; Quinn et al., 2014). Nevertheless, in a recent study by Hemelrijk et al. (2015) the authors have showed how swimming efficiency is increased in general when swimming in formation, when compared to the case of isolated swimming. The authors compared the results of their model in in-line, phalanx (side-by-side), rectangular and diamond configurations. They concluded that instead of the diamond as predicted by Weihs (1973) theory, the best arrangement was the in-line one. The work by Marras et al. (2015) showed that even when the fishes were swimming at the front of the school, they experienced and enhanced efficiency, and

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in fact it seemed always convenient energy-wise to swim in groups. More recently Ashraf et al. (2016, 2017) have shown how over a certain current speed, fish tend to arrange themselves in side-by-side positions in order to reduce their power consumption for balancing the imposed drag. Experiments on a small shallow water tunnel indicated that not only fish tend to swim in that specific geometrical arrangements, but also they preferred to beat synchronously their tails either in-phase or out-phase. Previous to that work Svendsen et al. (2003) and Herskin and Steffensen (1998) show how fish reduced tail beating frequency when in formation without changing their speed, indicating an efficiency increase due to the schooling behaviour.

As shown in the above paragraph, extensive literature exists if the analysis of wake interactions between swimmers is done with live fish. Numerical, theoretical and experimental work using simplified kinematics to study the complex fluid–structure interactions underlying the swimming of fish, are now wide spread. The use of canonical systems to model the kinematics of fish allows to isolate variables that cannot be controlled in experiments with live fish. Models of fish schools based on flexible foils are wide spread and multitude of results are available in the open literature. Park and Sung (2018) have recently studied the interactions between four individuals in different geometrical arrangements, including tandem, triangular and diamond configurations. The interactions between the foils and the vorticity generated by the school resulted in some of the configurations studied, in efficiencies being increased more than 35%. Gazzola et al. (2011) described a numerical method with which advanced computations were carried out with single and multiple swimmers. In the recent computations by Gazzola et al. (2016) and Novati et al. (2017), the authors have included optimisation capabilities thanks to reinforced learning concepts, and have shown how in the case of free swimmers without feedback interactions, the school can result in an unstable configuration. The simulations by Daghooghi and Borazjani (2015) made the authors conclude that the cost of transport of fish swimming in school could be highly improved, as the tail beat frequency in schools was consistently reduced when compared to the isolated swimming. The work by Dong and Lu (2007) described the forcing and the wake structures behind undulating foils, after numerical simulations in which separation distance and wave speed undulations were varied.

Most of the previous studies are based on models thought for the study of fish schools, and the topic of bio-inspired propulsion systems made of several foils in proximity, has practically received no attention although they are highly related. The numerical studies conducted on pitching and heaving airfoils by Tuncer and Kaya (2003) and Kaya et al. (2009), focused on the study of the thrust production of a biplane configuration. They concluded that by flapping out-of-phase, the system increased its capability to produce thrust by more than a 20% respect to one of the airfoils being isolated. Dewey et al. (2014) conducted experiments with a system of two pitching foils for different spacing and phase differences. They confirmed a progressive decay of performance of the pair as the separation was increased. The same trends in the propulsive performances were observed at all separations, depending on the phase difference, that dictated the ability of the system to produce thrust and the energy required for it. Bao et al. (2017) studied the performance of two two-dimensional pitching foils in out-of-phase flapping mode at various spacings. The authors found how propulsive efficiency was increased considerably for the cases with strong wake interference, respect to the case of the isolated foil.

Here, a simplified robotic system is used to parametrically study the effects of the relative position of two flapping systems in their overall propulsive performance. The intention is not only to shed more light to the case of individuals swimming in close proximity, but to have an experimental set-up that allows the study of the combination of a pair of foils in a single propulsion system. In this sense, the configuration is similar to that studied by Dewey et al. (2014) and Bao et al. (2017), with the difference that slightly staggered positions have also been investigated here, as representative of symmetry breaking cases. Detailed force measurements and flow quantification are used, and the results are compared to the ones obtained with a single flapping system for reference.

2. Experimental methods

The flapping system designed for the experiments, consists of two identical robotic devices that allow to control independently the pitch motions of two rigid foils submerged in water. Each flapping system is based on a servo motor able to generate torques up to 0.7 Nm when powered at 6 V, and had a 6 mm shaft connected to it through a rigid coupling. The main shaft was geared to a precision potentiometer that outputs the angular position of the shaft at all instants. A rigid coupling links the main shaft of each flapping device to a torque load cell. The other end of the load cell is rigidly linked to the second part of the shaft, in which the foils are installed. The foils are clamped to the 6 mm shaft by means of a 3D printed part, that smoothly changes from the circular shape of the shaft to the foil. The kinematics of each flapping foil can be independently controlled thanks to a micro-controller system programmed to allow sinusoidal oscillations of the foils. For the study presented here, the foils were made of 1 mm thick aluminium plates, considered to be infinitely rigid, with a span (s) of 150 mm and a chord (c) of 85 mm.

The two flapping devices were installed in an aluminium frame that allowed changes in the relative position between them as needed. They were rigidly coupled by means of a beam that hung from a 6 axis load cell, used to measure the forces generated by the robotic system when flapping. The multi-axis load cell was installed hanging from an air bearing carriage, with one of its measurement directions aligned to the air bearing guiding beam, in order to directly measure the thrust force generated by the system. The Cartesian coordinate system defined had its origin at the mid span point of one of the foils, with z along the main rotating shaft and the x aligned to the direction imposed by the air bearing rig. The air bearing consisted of a rectangular beam of cross-section 50.8×50.8 mm^2 with a local straightness accuracy of 25 μm/m