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On the effects of tip deflection in flapping propulsion

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ABSTRACT

The research described in this paper is inspired by the fact that nature's flyers and swimmers use a wide variety of control mechanisms in order to produce the impulse and the thrust required in each situation they are involved in. This control is made through complex passive and active mechanisms that are used to impose the desired momentum transfer in their wake.

Experiments have been performed with a flapping system that allows to set different inclinations to the tip of a robotic fin. Direct force measurements and Digital Particle Image Velocimetry (DPIV) have been used to study the propulsive performance for the different tip configurations investigated. The effects of the geometry of the tip and the kinematics imposed to the fin on the impulse generated, are discussed in detail. We show how the capacity of the system to produce impulse can be altered by imposing certain tip geometries that imply small local changes of the trailing edge. The modified tip geometries are closely related to the way vortices evolve in the near wake region and therefore how momentum is transferred to the wake. We have found that the configurations that produce the highest impulses have the tip deflected to the suction side of the system while flapping. The dynamic control of the tip allows changes in the impulse generated.

1. Introduction

Nature's flyers and swimmers are characterized by complex kinematics, governed not only by passive bony or cartilaginous structures, but also by active ones and tissue such as muscles. There has been a wide interest in the recent years focused on understanding the physical mechanisms underlying flapping propulsion, because of the implications this topic has in engineering. The role of passive flexibility in flapping propulsion has received considerable attention in the last decade as it is well known that insect wings are mainly passive (Dudley, 2000). Swimming species exhibit a wide range of mechanisms to produce the hydrodynamic forces that ultimately lead to their propulsion. Some of these mechanisms are based on complex kinematics of compliant appendages (Bainbridge, 1963). Parts of the propulsion appendages of fish are passive (i.e. cartilage and bone) but others are active based on different types of muscle tissue. These complicated biological systems have the ability to allow time-varying and spatial changes of curvature and stiffness, in order to provide the adequate thrust and manoeuvrability, according to the different needs posed by the environment or the situation. It was suggested by Alexandre (1965) that sharks actively modify the kinematics of their tail by changing curvature and stiffness using the radialis muscle. Flammang (2010) conducted a series of experiments using electromyography and electrical stimulation techniques to record muscle activity during swimming. The author found how the radialis muscle was actuated at precise

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timings respect to the caudal peduncle motions, and more specifically at higher swimming speeds that implied larger drag, indicating these muscles provided active control of curvature and stiffness for improved thrust.

The use of simplified numerical and experimental systems to simulate certain aspects of flapping propulsion, without the need for studying specific species, is very common . Low-order models have been used as a way to simplify continuous systems, in order to study the effects that flexibility has on propulsion. In the works by Toomey and Eldredge (2008) and Eldredge et al. (2010) the authors used a two linkage mechanism connected by means of a torsion spring to study flexibility effects on the aerodynamic performance of their system. They imposed different kinematics to their articulated wing and computed the aerodynamic forces and power involved in its motion, finding that in general flexibility reduced the power consumption of the system. Vanella et al. (2008) used a similar configuration but with a considerably larger mass ratio (structural mass to fluid mass) with which they could see improvements too, for certain spring stiffness configurations. The role of stiffness has also been investigated in airfoils having only certain parts flexible with the rest being rigid. Heathcote and Gursul (2007) and later on Cleaver et al. (2014) studied the effects of a flexible trailing edge of different sizes and stiffness on a plunging airfoil reporting thrust enhancements over 25% respect to the rigid case. Gerontakos and Lee (2008) and Lee and Su (2011) actively controlled the flap of an airfoil to dynamically change its camber allowing different stall properties. Medina et al. (2015) studied several wing configurations with deflections at the tip or at the root in hovering flight, and compared it to the performance of a rigid airfoil.

From the three-dimensional perspective, the effect that the vortices produced at the edges of the foil is still not totally understood, but it is clear that influences the forcing on the system based on the aspect ratio of the foil (Raspa et al., 2014). Fundamental studies with translating flat plates in starting-flow experiments were conducted by Ringuette et al. (2007) to study the effect of the tip vortex and its contribution to the forces generated during the motion of a flat plate in still fluid, in a simplified experiment designed to better understand hovering flight configurations. The authors investigated the effect of the aspect ratio of the plate on the tip vortex and leading edge vortex formation with the drag forces and the flow fields generated. A similar study but with low aspect ratio plates rotating, was conducted later on by DeVoria and Ringuette (2011).

The aim of the work presented here, is to demonstrate how the impulse produced by a canonical flapping system such as a rectangular pitching foil, can be modified by altering the very last part of the foil near the trailing edge or the tip. Also, to find out to what extent modifications of the tip are able to produce changes in the propulsive performance of the flapping foil system. In a series of preliminary periodic flapping experiments, Huera-Huarte and Gharib (2014) observed how rotational speeds (frequencies) and phase differences between the rotations of the fin and the tip, played a major role in thrust generation. In such a system, the vast parameter space that needs to be covered in order to study propulsive performance, makes the problem very complex, and this is why in this work, the number of variables to be explored has been reduced considerably. The kinematics have been restricted to single strokes as in starting-flow situations, instead of periodic flapping. Moreover, in order to study the effects on propulsion of the geometrical parameters of the tip, such as its length and inclination, without having the effect of its kinematics relative to the fin, a fixed tip configuration has been initially used. The work is focused on the analysis of the impulse generation capabilities when producing single stroke rotating motions, as a way to fundamentally understand how propulsion changes and its relationship to the vortex dynamics in the wake. In the last part of the work several active tip configurations are also investigated.

2. Experimental methods

The first set of experiments, that appears described in Section 2.1, was conducted with plates having fixed deformations at their tip. This system allowed the investigation of the kinematics and the geometrical effects on the propulsive performance of the system. A second set of experiments, described in Section 2.2, was conducted with a system having its tip articulated, allowing the tip to be controlled independently of the fin.

2.1. The fixed tip flapping system

In the fixed tip set-up, the robotic model used for the experiments, is based on a single servo motor that produced pitch motions of different rigid plates attached to a shaft (main servo shaft). As it will be explained in the following section, this shaft acted also as the main shaft in the dynamic tip set-up. All foils had a span (s) of 150 mm and a chord (c) of 85 mm, and were made of 1 mm thick aluminium sheet. The same span to chord ratio (s/c) of 1.76 was used for the experiments with the active tip system described in the following section. During the experiments, we systematically varied the length (c_t) and the angular deflection (θ_{t_0}) of the tip. The total swept angle ($2\theta_{f_0}$) and the angular velocity (Ω) which was forced to be constant during most of the experiment, were also varied. A total of seven tip angles θ_{t_0} were tested, with values of −60, −45, −30, 0 (flat plate or fin without tip deflection), 30, 45 and 60 deg. The negative sign on the tip angle indicates that the tip is behind the motion of the fin during its motion (inclined to the suction side). For the −45 deg tip configuration, three tip lengths were studied, leading to tip to chord ratios ($\frac{c_t}{c}$) of 0.08, 0.17 and 0.34. Finally for each foil, four different swept angles ($2\theta_{f_0}$) were imposed, each with several angular velocities, producing variations of Reynolds number (Re) up to approximately 30 000. The Reynolds number is defined here, based on the velocity of the fin at the starting point of the tip ($U_b = \Omega c_f$) and the total chord of the foil ($Re = U_b c/\nu$). c_f is the chord of the fin up to the base of the tip ($c_f = c - c_t$). An schematic of the fixed tip fin appears in Fig. 1. The figure shows the initial and the final position of the fin rotating around the main servo shaft.