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Effect of chordwise flexibility on pitching foil propulsion in a uniform current

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ABSTRACT

The role of the chordwise flexural stiffness in a rectangular foil undergoing pure pitching has been investigated experimentally. Digital Particle Image Velocimetry (DPIV) and load measurement with a 6-axes balance have been done to study the flow patterns and hydrodynamic forces around the flapping flexible foils. We have found a transition of thrust generation in the $semi-flexible$ foil with $\theta_0 = 72^\circ$ for all the Re studied between the range of $0.25 \le St \le 0.6$ where it is known that maximize the thrust by a flapping foil. As a result, the optimum flexural stiffness has been determined with a $semi-flexible$ foil up to 69% efficiency for $\mathrm{Re} = O(10^4)$.

1. Introduction

Animals have developed for millennia the ability to optimize their propulsion with high efficiency in water or air. Features such as high velocities, sharp turning maneuvers, rapid acceleration, turbulence control and drag reduction, fit perfectly with the design for autonomous underwater vehicles ($AUV\ s$). The diversity of AUV applications is increasing in a wide range of fields, which are divided into four areas; land management, commercial, earth science and homeland security. These applications recently have increased the attention on the flapping propulsion at low Reynolds numbers ($\approx 10^4$). The development of high propulsive performances in nature has brought an extensive research using experimental and numerical techniques.

The first research on thrust for an oscillating rigid airfoil was carried out by Knoller (1909) and Betz (1912). In the middle of the 1930s a theoretical explanation was given about the different patterns of a large-scale drag wake and a thrust wake, von Kármán and Burgers (1943). Following these studies, theoretical models by Garrick (1937), Lighthill (1975), Wu (1971a) and Chopra (1976) under oscillating foils in inviscid flow were performed. An important advance was achieved by Triantafyllou et al. (1993), where the range of propulsive efficiency between $0.25 \le St \le 0.45$ was found using a two-dimensional linear stability analysis on the wake of a pitching foil. More recently research papers have been focused numerically with an unsteady panel method (Cebeci et al., 2005), Navier-Stokes simulations (Wu and Sun, 2004) or Brown and Michael model (Guglielmini et al., 2003).

Experimental studies of flapping foils have focused on finding out high efficiencies (Anderson et al., 1998; Schouveilera et al., 2005; Esfahania et al., 2013, 2015), the effect of the oscillating modes (Read et al., 2003; Hover et al., 2004), aspect ratios (Jones et al., 2002), different patterns in the wake (Koochesfahani, 1987; Buchholz and Smits, 2006, 2008; Schnipper et al., 2009; Green et al., 2011) and flapping under ground effect (Blevins and Lauder, 2013; Quinn et al., 2014; Fernández-Prats et al., 2015).

The beginning of the theoretical investigations with a flexible propulsor started with the use of the linear theory by Wu (1971b) as well as inviscid theory (Katz and Weihs, 1978, 1979; Bose, 1995; Liu and Bose, 1997; Ramamurti et al., 1999). It was found that flexible propulsors (low levels of deformation) were achieving better efficiencies compared to a rigid propulsor with a small penalty to the thrust. In addition to the investigation of efficiencies of flexible propulsor (Miao and Ho, 2006), deformable passive bodies have been analysed using the incompressible Navier-Stokes equations (Bergmann and Iollo, 2010) and the multiblock lattice Boltzmann method (Zhang et al., 2010).

Despite the important role of flexibility in the animals wings or fins (Triantafyllou et al., 2000), the stiffness of insect wings when they are flying is still unclear (Maxworthy, 1981). A few studies have quantified the deformation of the biological structures involved in locomotion. In the case of insects, flapping, flexion and the flexural stiffness has been studied with the influence of wing venation as well as the dynamic bending (Combes and Daniel, 2001, 2003a,b). In the case of fish, there is not yet available a suite of data for flexible propulsor (Lauder et al., 2006). Yamamoto et al. (1995) studied an oscillatory propulsion control system with different flexibilities of fins as a vehicle actuator in ship models. Fins with seven flexibilities were tested, the fin with 15% rigidity obtained the best efficiency of up to 31%. The effect of chordwise

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flexibility undergoing pitching, heaving and both motions has been studied experimentally by Prempraneerach et al. (2003), Heathcote and Gursul (2007), Zhao et al. (2009) and Barannyk et al. (2012). Prempraneerach et al. (2003) found a 36% increase in efficiency compared to a rigid foil, with a small loss in thrust. Heathcote and Gursul (2007) ascertained benefits in the efficiency and noticed that the strength of vortices is slightly larger for the flexible foil compared to the rigid one and substantial differences in the Reynolds number. Forces in flapping wings were studied by Zhao et al. (2009) finding aerodynamic forces that can be controlled by altering the trailing edge flexibility of a flapping wing and thereby controlling the magnitude of the leading edge vorticity.

More recently, Shin et al. (2009) numerically and Quinn et al. (2013) experimentally suggested an increased of thrust and efficiency of a flexible heaving foil is attributed to the change of the trailing edge amplitude.

The main goal of the current work presented is to demonstrate how the flexural stiffness of a pitching foil is able to modify the amplitude of the tip for a kinematic sets in order to maximize the efficiency. The study is approached from purely physical consideration, in a simple way, different flexibilities of the caudal fin of a fish. The set-up allows to simulate a wide variety of situations by combining flow speed and the foil kinematics. Experimental measurements of the thrust, efficiency and time-resolved velocity flow fields are analysed. Hydrodynamic forces of foils at different flexural stiffness are evaluated to define the high efficiencies to produce drag-based propulsion.

In Section 2 the experimental methods is described. In Section 3 results and discussion of hydrodynamic forces are presented to investigate the effects of flexibility on propulsive force acting on a pitching foil. Finally, the conclusion are provided in Section 4.

2. Methods

2.1. Experimental set-up

Experiments were conducted in a towing tank of 2 m long with a square section of dimensions 0.6×0.6 m^2. The water tank was equipped with a towing carriage that can move along a two-rail system (Fig. 1a). The towing carriage was driven by a geared electric motor that could be controlled in order to produce the desired towing speeds (U). A rotary potentiometer installed in the shaft of the motor, allowed closed loop control of position (Fig. 1a).

The flapping model was set up on the carriage of the towing tank attached to a 6-axes balance. The pitch motion imposed to the flapping device was produced by a stepper motor and consisted of a sinusoidal motion that can be approximated following equation (1).

$$\theta(t) = \frac{\theta_0}{2} sin\,(2\pi f t), \tag{1}$$

where f is the flapping frequency and θ_0 is half of the swept angle of the pitch motion. The angular position of the flapping foil motion was measured using a digital encoder. Hydrodynamic forces and moments were measured with a 6-axes balance coupled to the main shaft of the system (Fig. 1c). Foils were clamped to the a shaft (pivot point) with a streamlined coupling allowing only chordwise deformation. The distance from pivot point to the tip was 11.5 cm (l). The system was set in a way

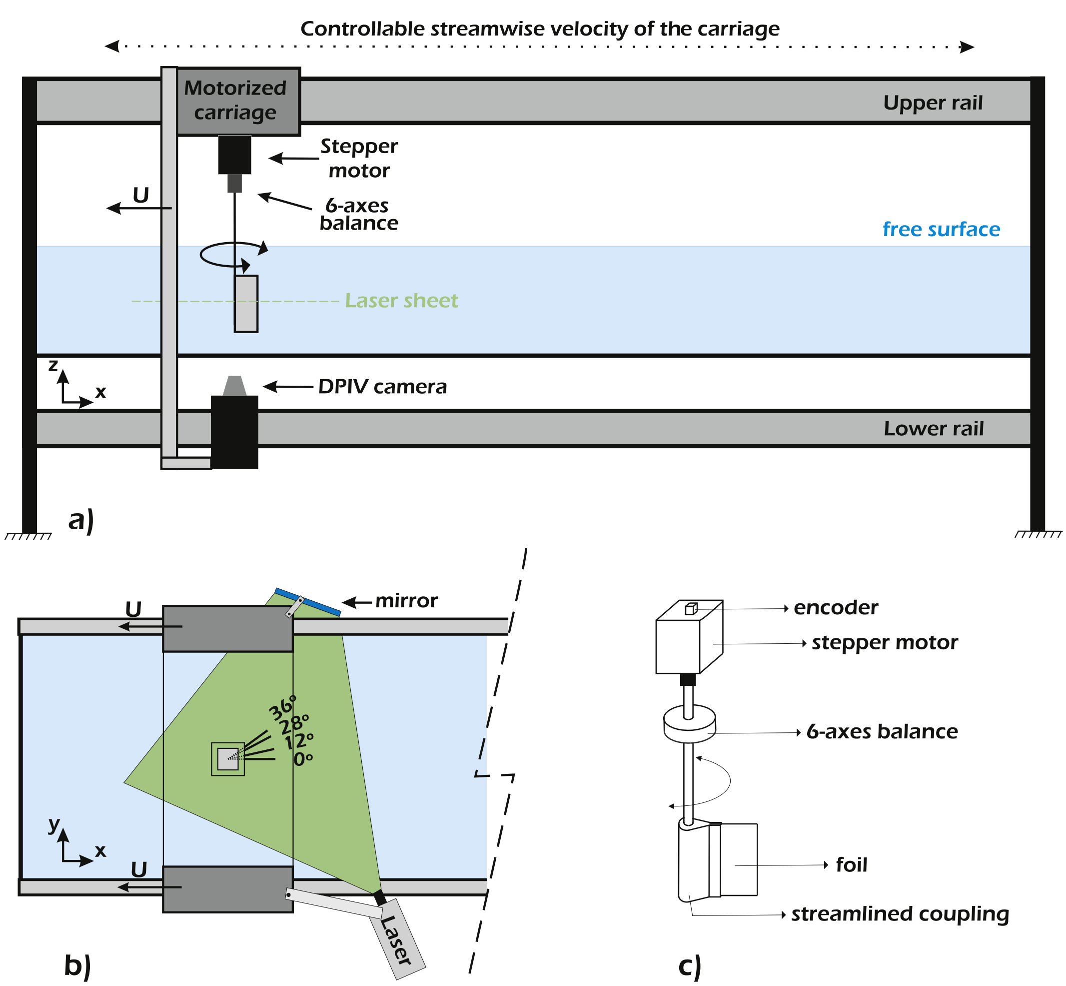

Fig. 1. a) Side view of the experimental set up. b) Top view of the experimental set up. c) Apparatus.