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Effect of the stiffness, inertia and oscillation kinematics on the thrust generation and efficiency of an oscillating-foil propulsion system

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ABSTRACT

This paper presents an experimental study that has investigated the effects of the foil stiffness, inertia and oscillation kinematics on the thrust generation and efficiency of a flexible oscillating-foil propulsion system. A semi-empirical damped-oscillator model, which included a quadratic damping element, was developed and fitted to the experimental results. The model was used to develop explanations for the observed trends in the propulsive performance. For all of the foils constructed for the study, a consistent relationship between the efficiency and frequency ratio was observed. The maximum efficiency occurred at the same frequency ratio that resulted in both a beneficial phasing of the deformation with respect to the driven motion and also the maximum overall amplitude of the motion. For foils of equivalent resonant frequency operating at the same frequency ratio, the stiffer and heavier foils were found to develop greater thrust, likely because the lower effective damping allowed for a greater amplitude of the motion. Increasing the amplitude of the driven motion was found to cause the frequency ratio providing the maximum efficiency to shift towards lower values. The use of combined pitch and heave motions was shown to increase efficiency while reducing thrust compared to the heave-only case.

1. Introduction

There has recently been renewed interest in the use of oscillating foils instead of conventional rotating propellers as propulsion mechanisms for aquatic and aerial vehicles. Because the locomotion of birds, fish and insects is based on oscillating foils, it is expected that this novel design offers the potential to achieve the very high degree of maneuverability observed in natural flyers and swimmers, which is yet unmatched by man-made vehicles (Jones et al., 2005).

Much of the recent research in the field of oscillating-foil propulsion has focused on the effects of using flexible foils, which under suitable conditions have been demonstrated to achieve better propulsive performance than rigid foils. However, the current understanding of the physics of flexible oscillating foils does not yet offer specific guidelines to the designers of propulsion systems for the selection of suitable combinations of structural properties and oscillation kinematics to achieve high propulsive performance. The work in the current paper aims further to the existing knowledge by

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considering the effect of the foil stiffness, inertia, resonant frequency and oscillation kinematics on the thrust generation and efficiency.

1.1. Background

An oscillating foil propulsion mechanism drives the foil in the surrounding fluid in either a reciprocating motion referred to as heaving, a rotating motion termed pitching or a combination of heaving and pitching motions.

It has been theoretically shown (Triantafyllou et al., 1993) and experimentally demonstrated (Anderson et al., 1998) that propulsive oscillating foils act to apply disturbances to the flow of the surrounding fluid which are amplified by the unstable wake into a thrust-producing jet. The stability of the wake is therefore one of the main physical phenomena governing the operation of an oscillating foil. Amongst other parameters, the Reynolds number, Strouhal number and the ratio of the heave amplitude to the chord, h_0/c, which are known to affect the stability of the wake, are important dimensionless groupings affecting the performance of oscillating foils (Triantafyllou et al., 2004). The Reynolds number and Strouhal number are defined by Eqs. (1) and (2) respectively as follows:

$$\mathrm{Re} = \frac{Uc}{\nu}, \tag{1}$$

$$\mathrm{St} = \frac{fA}{U}, \tag{2}$$

where U is the flow velocity, c is the chord length, ν is the kinematic viscosity and f is the oscillation frequency. The width of the wake, A, is conventionally taken as twice the heave amplitude, h_0. The disturbances amplified by the wake form large-scale vortices, which are arranged in a reverse Kármán street. This flow pattern has a jet-like momentum profile in a time-averaged sense (Triantafyllou et al., 1993). As an alternative explanation for the force generation of oscillating foils, the relative velocity between the foil and the fluid can be understood to result in a lift force, which is directed to provide forward thrust, a phenomenon referred to as the Knoller–Betz effect (Jones and Platzer, 2009).

Since the objective of a propulsion system is to produce an adequate thrust force with the minimum power input, it is useful to define the thrust and power coefficients, given by Eqs. (3) and (4) respectively, to quantify the performance of flexible oscillating foils (Anderson et al., 1998):

$$C_T = \frac{F}{\frac{1}{2}\rho U^2 S_o}, \tag{3}$$

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 S_o}, \tag{4}$$

where F is the streamwise force, ρ is the fluid density, S_o is the planform area and P is the input power used to drive the oscillating motion. The propulsive efficiency is given by the ratio of these two quantities (Anderson et al., 1998):

$$\eta = \frac{C_T}{C_P}. \tag{5}$$

In an early work by Katz and Weihs (1978), simulations were used to demonstrate that a flexible oscillating foil had the potential to achieve higher efficiency than a rigid foil with the same oscillation kinematics because the deformed shape of the flexible foil directed the net force to be more closely aligned with the direction of travel. Similar results were found experimentally by Barannyk et al. (2012). However, other works (Heathcote and Gursul, 2007; Michelin and Llewellyn Smith, 2009; Ramananarivo et al., 2011; Spagnolie et al., 2010; Wu et al., 2011) have shown that under certain conditions more rigid foils actually achieve higher performance. Generally, in these works, it was found that the best performance is achieved when the degree of flexibility is chosen so that the passive deformation occurs at the appropriate phase with respect to the driven motion (Ramananarivo et al., 2011; Spagnolie et al., 2010) or provides the greatest amplification of the input motion (Michelin and Llewellyn Smith, 2009).

Because the deformation of a foil is a dynamic process, the deformation behavior is influenced by the inertia as well as the static stiffness (Combes and Daniel, 2003; Thiria and Godoy-Diana, 2010). Together, these parameters set the resonant frequency of the structure. Consequently, the frequency ratio, or ratio of oscillation frequency to resonant frequency, becomes a second important dimensionless frequency in addition to the Strouhal number when considering the performance of flexible oscillating foils.

Investigations of flexible oscillating foils that have explicitly considered the effects of inertia are generally limited to numerical studies because it is difficult to change the inertia of a physical structure without also influencing its stiffness or geometry. The results of these simulations have, however, confirmed that the inertia is indeed a significant structural parameter affecting the propulsive performance. For instance, the results of Yin and Luo (2010) have shown that for foils of equivalent resonant frequency operating at the same frequency ratio, less massive and more flexible foils generally achieve better propulsive performance. Similar results were reported by Zhu (2007), who found that increasing the inertia of a chordwise-flexible foil resulted in phasing between the driven motion and the deformation which was not conducive to thrust generation.