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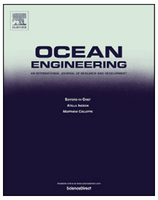

Semi-active flapping foil for marine propulsion

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ABSTRACT

The present study deals with numerical investigation of a semi-active flapping foil of which the kinematics is characterized by an imposed heave motion and a free pitch motion. A torsion spring is attached to the foil and acts to restore the foil parallel to the advance velocity. The prescribed flapping foil has been simulated using a boundary element method in combination with a Newton-Euler solver in order to study the influence of flapping frequency and spring stiffness on the propulsive performance. The spring stiffness has strong influence on the induced pitch angle and the effective angle of attack which consequently determines the openwater characteristics. The stiff spring resists the foil from pitching resulting in high heave force, while the more elastic hinge leads to drag generation at the end of each stroke. The results demonstrate that the semi-active flapping foil attached to an appropriate torsion spring performs efficiently over a wide range of advance ratio like a controllable-pitch propeller. The best efficiency is found for a Strouhal number and a pitch amplitude as reported in biological researches. The numerical results also imply that the resonance seems to have less influence on the propulsive performance.

1. Introduction

Marine vessels mainly spend their time operating at nearly constant speed. Therefore, the steady propulsion conditions are generally optimized for efficiency. This type of vessels is usually equipped with a fixed-pitch propeller optimized for a certain speed and load. However, some types of vessels may operate within a wide range of load or resistance, e.g., fishing boats with purse seine or trawl. Basically, fishing operation comprises of two main activities: sailing and trawling, resulting in at least two different resistance curves (Notti and Sala, 2012).

This kind of operating vessel requires a controllable- or a variable-pitch propeller to maintain its optimal operating condition since this type of propeller is efficient for wide ranges of speed and load. However, a variable-pitch propeller is costly, complicated, and frail compared to a fixed-pitch propeller, hence seemingly unaffordable for fishing boats. As a result, the propulsion system of a fishing boat typically consists of a diesel engine and a fixed-pitch propeller which delivers its best efficiency only at a specific condition. This leads to a drastic decrease of propulsive efficiency when operating at other different conditions.

Mimicking aquatic animal fin or tail kinematics is potentially one of the most interesting concepts to improve the performance of ships and underwater vessels, especially ships with large variable loads. This is because the bio-inspired flapping foil is naturally equivalent to variable-pitch propulsion system (Floc'h et al., 2012). In addition, cavitation characteristics of flapping foil propulsors is said to be more acceptable than that of conventional propellers (Rozhdestvensky and Ryzhov, 2003). Therefore, the use of flapping foil can be an alternative choice for propulsion system.

The evolution of our understanding on flapping foil mechanism has progressed over decades through a combination of observations, experiments and numerical simulations. Since 1970s, a large number of works have been performed to study unsteady mechanisms of oscillating foil used for propulsion (Scherer, 1968; Lighthill, 1970; Wu, 1971; Webb, 1975; Grebeshov and Sagoyan, 1976; Archer et al., 1979; Morikawa and Isshiki, 1980). Several studies based on observation from the natural world (Bose et al., 1990; Fish, 1998; Taylor et al., 2003) have concluded that the operating conditions of aquatic animals are within a certain parametric range. Using the heave amplitude as the reference lengths, the Strouhal number is reported between 0.2 and 0.4, whereas the pitch amplitude is found between 20° and 40°. The operating conditions of flapping fins, wings or tails have been confirmed by theoretical analysis (Eloy, 2012), experimental studies (Triantafyllou et al., 1993; Anderson et al., 1998; Read et al., 2003; Schouveiler et al., 2005), and numerical investigations using different methods, e.g., BEM (Floc'h et al., 2012;

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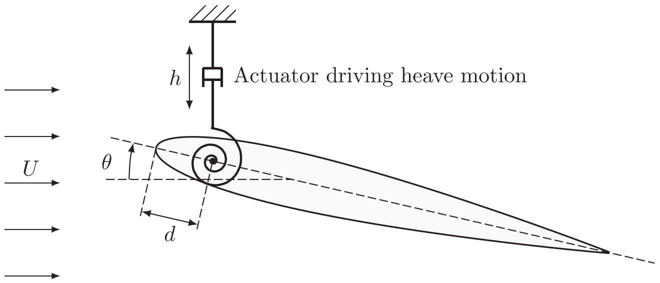

Fig. 1. Schematic illustration of the semi-active flapping foil with forced heave motion. The pitch angle $\theta(t)$ is induced by hydrodynamic force.

Politis and Tsarsitalidis, 2009) or RANSE (Thaweewat et al., 2009). Mostly, both the heave and the pitch motions are prescribed by simple harmonic functions which are useful in parametric space studies despite the model simplicity. The results are in satisfactory agreement with the comparable observations. Particularly, the regimes of operation closed to the observed parametric ranges give the optimal performance. Unsurprisingly, this implies that aquatic animals have evolved toward hydrodynamic optimization.

A small number of works have been performed for comparison between the performance of flapping foil propulsor and a conventional marine propeller since the parameterization of both devices are different. The hydrodynamic performance of a conventional propeller is traditionally presented in functions of advance ratio which is the ratio between the translational distance the propeller moves forward during one revolution and the propeller diameter, whereas that of flapping propulsor is typically expressed in terms of Strouhal number. Nevertheless, Hoppe (1989) has introduced dimensionless numbers making the comparison unbiased, and has concluded that the efficiencies of both devices are approximately on par. However, a comparison on propulsive efficiency between oscillating cetacean flukes and a conventional propeller (Fish and Lauder, 2006) has showed that the former is superior. This is likely due to the fluke elasticity.

Another numerical investigation based on BEM simulations (Floc'h et al., 2012) has introduced a comparison between the two regimes. It has been concluded that the bio-inspired propulsive foil can be used as a propulsion system since its efficiency is comparable to that of an efficient propeller in openwater. The study has also reminded the disadvantages of the flapping foil, e.g., strong forces fluctuation and mechanical complication since the motion is prescribed with two degrees of freedom: heaving and pitching. The former disadvantage can be avoided by operating several foils at different phase, while the latter disadvantage could be alleviated by the use of semi-active flapping foil (Murray and Howle, 2003). This results in a simple one-actuator input which is less complicated compared to a two-actuator system. However, the study (Murray and Howle, 2003) is questionable since the foil is actively actuated in the pitching direction and therefore passively driven in heaving direction which is the kinematics used for energy harvesting (Deng et al., 2015; Teng et al., 2016). A flapping foil used for energy extraction generally gives drag instead of propulsive thrust.

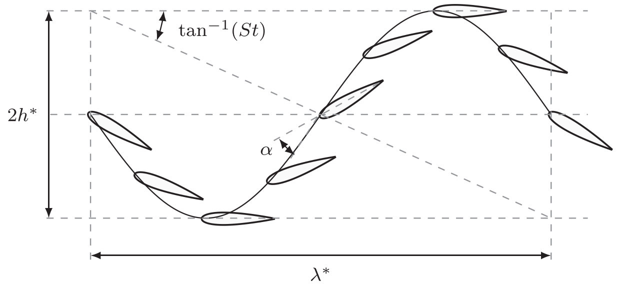

Fig. 2. Schematic representation of the foil kinematics along with dimensionless parameters. The spline represents path line of pivot location of the foil. The effective angle of attack can be calculated as: $\alpha = \theta - \tan^{-1}(\dot{h}/U)$.

The mechanism of semi-active flapping foil has also been aerodynamically investigated in insect flight. Different aerodynamic tools, BEM and RANSE, used to simulate unsteady flow around insect flapping wing, have shown good agreement (Willis et al., 2008). In order to efficiently generate thrust, it is recommended to maintain attached flow in flapping kinematics to minimize separation effects and kinetic energy lost to the surrounding fluid (Willis et al., 2007). However, the influence of torsion spring attached to the foil has not been studied and discussed in detail. In addition, the spring coefficient used in these studies is not non-dimensionalized, while investigations in fluid dynamics commonly use dimensionless variables since matching the dimensionless numbers is a key to achieve validity and similarity of simulations.

In ship design, the hydrodynamic properties of propulsive devices, i.e., the openwater characteristics, are necessary for optimizing the propulsion system. However, few works have been done to provide such data of flapping foil propulsors. The objective of the present research is to hydrodynamically study the propulsive characteristics of semi-active flapping foil and to provide the necessary hydrodynamic information of such propulsion system. Particularly, the influence of the torsion spring stiffness on propulsive performance will be investigated. Furthermore, the openwater characteristics of the foil will be presented in functions of advance ratio similarly to that of conventional marine propeller in order to be able to compare the both systems.

2. Principles of semi-active flapping propulsion

In the present study, a foil with NACA0012 profile section is attached to a torsion spring allowing the pitch motion of the foil as illustrated in Fig. 1. The torsion spring is used to restore the foil toward the horizontal plane. The foil is subjected to move horizontally with a constant advance velocity U and to heave vertically with a simple harmonic function $h = h_0 \sin(2\pi f t)$ at its pivot point. Consequently, the sinusoidal heave motion together with the advance velocity creates an oscillating hydrodynamic force and moment causing the foil to pitch. In addition, the foil is not allowed to move in any other degrees of freedom.

2.1. Flapping parameterization

The flow around the flapping foil and the foil kinematics can be characterized by dimensionless parameters. The dimensional analysis enables a systematic investigation of the influence of different foil kinematic parameters on the openwater performance. The main dimensional variables are the flapping frequency f, the heave amplitude h_0, the advance velocity U, the foil geometry: span b and chord c, the fluid density ρ, the foil moment of inertia I, the torsion spring stiffness K and the location of pitching axis measured from foil leading edge d. However, it should be pointed out that the influence of inertial mass in heaving direction is not taken into account since the foil motion is directly imposed.

By applying the Buckingham theorem, the openwater characteristics such as the efficiency η can be defined as a function of dimensionless parameters:

$$\eta = \phi\left(\frac{U}{cf}, \frac{h_0}{c}, \frac{b}{c}, \frac{d}{c}, \frac{I}{\rho c^5}, \frac{K}{\rho f^2 c^5}\right) \tag{1}$$

or

$$\eta = \widehat{\phi}(\lambda^*, h^*, \Lambda, d^*, I^*, K^*) \tag{2}$$

where the dimensionless heave amplitude $h^* = h_0/c$, the wing aspect ratio $\Lambda = b/c$ and the dimensionless pivot location $d^* = d/c$ are the dimensionless parameters concerning foil geometry and length. The dimensionless wavelength $\lambda^* = U/cf$ is the essential dimensionless