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Proposed kinematic model for fish-like swimming with two pitch motions

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ABSTRACT

In the present investigation a new kinematic model for a fish-like swimming is presented. In this model the foil has two rotational motions in order to approach of the fish swimming performance. This kinematic model is a generalized model for flapping foil because it introduces caudal-to-heave ratio (is ratio of caudal length to heave amplitude) which has not been considered. In the present work the proposed kinematic model can be evaluated in Cylindrical coordinate, while it involves with nonlinear hydrodynamic and propulsion models. This kinematic model can switch to Cartesian coordinate when the caudal-to-heave ratio is infinitive value. The foil experiences the diverse effective angle of attack profile due to the influence of the caudal length in association with other kinematic parameters. It is shown that increase in foil-pitch amplitude decreases the angle of attack and hence, thrust reduces in thrust-based condition. Extreme increasing of foil-pitch amplitude leads the angle of attack to switch to drag-based condition and high drag production results from these changes. Moreover, it is shown that in the limited caudal-to-heave ratio the foil may have the better propulsive performance with reasonable thrust. Furthermore, the optimum Strouhal number and foil-pitch amplitude for fish-like swimming are computed from 0.2 to 0.4 and from 30° to 40°, respectively, which are in agreement with observed results in the nature.

1. Introduction

The important quality determining the endurance of many fishes is the swimming performance. The aquatic species have developed highly efficient swimming mechanics. Based on the observations of fish and marine mammals, the scientists tried to develop vehicles whose endeavor attempt to mimic the swimming kinematics of the marine mammals. Among the fish swimming, the carangiform swimmer has the ability of maintaining high-speed swimming in calm water, whereas the anguilliform swimmer exhibits remarkable maneuverability in cluttered environments (Sfakiotakis et al., 1999). To inspire from nature of fishes and apply their mechanism in engineering field, scientists have tried to consider the tail of fish as main propulsor and this topic is entitled as flapping foil propulsion. The flapping foil is a moving tail (plate or foil-shaped) which oscillates frequently in order to produce thrust for propulsion. On the point of high level propulsive efficiency, stability and maneuverability, flapping foil with pure foil-pitch, pure heaving or combination of both motions have potential applications in the design of high efficient Unmanned Underwater Vehicle (UUV) (Rozhdestvensky and Ryzhov, 2003).

Until recently, many investigations have been done to understand the mechanism and kinematics of flapping foil. Pedro et al. (2003) conducted numerical study on the value of foil-pitch amplitude and they recommended the foil-pitch amplitude should be between 30° and 40°. Based on the pure observations of the animal world, Bose et al. (1990) and Taylor et al. (2003) during their experimental studies found that the maximum foil-pitch amplitude is between 20° and 40°. They also concluded that the most commonly observed Strouhal number is between 0.2 and 0.4. Furthermore, the experimental and numerical analyses of Anderson et al. (1998), Triantafyllou et al. (2000), Godoy-Diana et al. (2008), and Politis and Tsarsitalidis (2009) confirmed that a Strouhal number between 0.2 and 0.4 leads to the optimum efficiency. Additionally, Floc'h et al. (2012) compared the hydrodynamic performance of the biomimetic propulsion device with a conventional propeller. They also found an optimum efficiency for the Strouhal number from 0.2 to 0.7, and for a maximum foil-pitch angle between 30° and 60°.

On the point of heave amplitude, Fish (1998) observed that the heave amplitude has little influence on the thrust generation. Furthermore, an experimental study conducted by Anderson et al. (1998) stated that a too small heave-to-chord ratio reduces the

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efficiency. Floc'h et al. (2012) also noted that the heave-to chord ratio has no influence on the maximum efficiency. Other parametric studies have been also done in order to improve the propulsive performance of the flapping foil. For example, Guerrero (2009) has done a parametric numerical study to evaluate the effect of airfoil camber on the aerodynamic performance of rigid heaving airfoils. It is mentioned that the airfoil camber has the notable influence on the average lift coefficient, while it has the slight effect on the average thrust coefficient and propulsive efficiency of the heaving airfoils. Shin et al. (2009) employed the hybrid Cartesian/immersed boundary method to simulate the effects of flexibility on propulsive force acting on a heaving foil in the viscous flow. They showed that the flexibility of the heaving foil decreases the vertical force and improves the propulsion efficiency.

On the point of kinematic investigations, Wang et al. (2004) investigated on the unsteady forces in different kinematic patterns for a low Reynolds number, Ania (2008) considered a figure-of-eight-like kinematics which was obtained from a pair of counter rotating flapping blade configuration. This kinematic model is inspired from insects flying in the air. Subsequently, Amiralaei et al. (2011) considered this kinematic pattern to parametric study on the unsteady generated forces by flapping wing. They found that the strength, interaction, and convection of the vertical structures around the wing are notable influenced by the variations of the kinematic parameters.

On the point of flapping foil propulsion, the foil motion may be two or three dimensional. Two dimensional foil motion can be referred to heaving motion of foil with or without pitching in different motion trajectories (Esfahani et al., 2013; Triantafyllou et al., 1993; Triantafyllou et al., 2005). Three dimensional foil motion is similar to that of penguin wing, turtle fin or pectoral fin in fishes, and this type of motion consists on pitching and rolling of flapping foil (Esfahani et al., 2015; John et al., 2006; Kato, 2000; Karbasian et al., 2015). Two dimensional foil motion (with a certain aspect ratio and the same chord length through the wing) is the simplest flapping foil propulsion and the kinematic parameters along the span is the same value (Anderson et al., 1998). Therefore, the hydrodynamics stall and flow control will be represented in simple scheme and can be fairly considered with analysis of just one section from wing. On the other hand, this heaving motion has to be generated by translational motion at which the rotational motion almost converted to translational one using an appropriate mechanical mechanism.

Three dimensional foil motion has the simple mechanism with two rotational motion (pitching and rolling) which makes it more interesting than two dimensional one. But three dimensional foil motion offers different kinematics, hydrodynamic forces and flow conditions through the wing span, which makes it more complex to analysis (Techet, 2008). For example, during the rolling some sections of wing may fall in stall and drop the wing performance. The schematic diagram of moving and rotating axes is illustrated in Fig. 1. As it is shown, the foil can have translational motion (heaving) or rotational motions (rolling or pitching).

The present study proposes a new parameter which its importance has not been considered by other researchers. This parameter, which is named as the caudal-to-heave ratio, introduces a new two dimensional kinematic model in flapping foil propulsion. The caudal-to-heave ratio makes it possible to evaluate the propulsive performance of fish swimming. Furthermore, it is proposed to solve the problems of previous two and three dimensional foil motions. This two dimensional kinematic model has two rotational motions. One is foil-pitch and other is caudal-pitch. The caudal-pitch motion causes the foil to be moved in circular direction and this motion may affects considerably on the effective angle of attack profile during propulsion. Furthermore, introduced hydrodynamic and propulsion models are also presented that enhance the quality of kinematic model. The introduced model can be also used for a good prediction of hydrodynamic and propulsive performance of flapping foil. The present model may encourage engineers to design the more desirable bio-inspired or fish-like propulsors in near future.

2. The description of model and governing equations

2.1. Physical model

Some fishes have astounding abilities which have attracted attention of many scientists. Swimming speed and swimming time are considered for evaluating swimming ability of fishes. They may have high efficiency or high acceleration during locomotion. In the most recent works on swimming of fishes, the kinematics of foil is considered with rotational (foil-pitch) and translational (heave) motions. In contrast, most of fishes oscillate their tails in a circular direction and it may influence on the kinematics of swimming. Focusing on oscillating tail by fishes, most of the produced thrust originates at caudal tail and caudal area. Therefore, if length of caudal is considered constant, the motion of tail is on a circular direction. Fig. 2 shows schematically the motion of fish's caudal and tail.

Fig. 3 displays the motion of the flapping foil in two different motion patterns. In Fig. 3(a) the oscillation of foil is resulted by the involvement of translational and rotational motions which are known as heave and foil-pitch, respectively. The heave motion is up-down movement of foil with reference to centerline and foil-pitch motion is rotation of foil around its pitch axis. These two motions have significant effect on characteristics being considered in investigations on the flapping foil propulsion. The velocity of vertical heave (up-down) motion relative to the velocity of free stream fluid determines the Strouhal number, and the function of foil-pitch angle appears in the angle of attack profile during cyclic propulsion. This pattern of motion is defined as

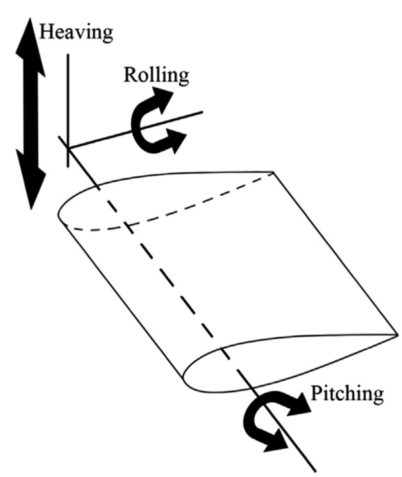

Fig. 1. Schematic diagram of moving and rotating motions of a foil. Heaving is translational motion and pitching and rolling are rotational motions.

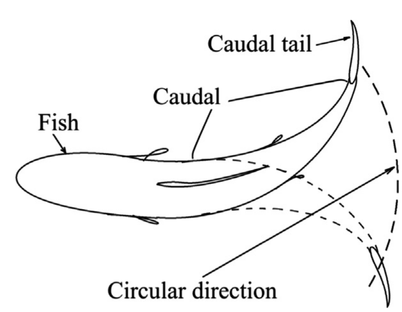

Fig. 2. The schematic of the fish during oscillation of caudal tail through circular direction.