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Energy extraction and hydrodynamic behavior analysis by an oscillating hydrofoil device

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ABSTRACT

In this paper, a modified model is proposed for an oscillating foil energy harvesting device, and the corresponding mathematical model is established too. A grid model for foil NACA0015 is built by using dynamic and moving mesh technology of the Computational Fluid Dynamics (CFD) software FLUENT. To understand the hydrodynamic performance and energy extraction capability of the modified model, the effects of motion parameters (heaving component parameters and pitching component parameters) are investigated. The evolutions of angle of attack and vortex field are examined. The results show that motion radius and heaving amplitude play important roles in impacting the time-averaged power coefficient. As the frequency increases, the peak value of the effective angle of attack is decline. The effect of pitching amplitude is gradually increased on the time-averaged power coefficient. Under the large frequency, the energy extraction efficiency is more sensitive to the motion radius and heaving amplitude. Moreover, there exists an optimal oscillation frequency to achieve a maximum time-averaged power coefficient for each pitching amplitude.

1. Introduction

With the increasing of energy consumption and the pressure for limiting greenhouse effect, renewable energy technology is sustaining a steady development due to society and governmental policies support. Tidal flows are important alternative of renewable power sources, because of the high energy density of flowing water and minimal environmental impact. This energy harvesting is generally obtained through turbines containing rotating blades [1]. Inspired by bird and fishes, the applications of flapping foils as energy harvesting devices have gradually attracted attention in recent decades [2,3]. Compared with conventional turbine that based on rotating blades, oscillating hydrofoil is more environmentally friendly and it has advantages in extracting energy from tidal current in shallow water [4,5].

Oscillating hydrofoil with pure pitching motion or combination of both heaving and pitching motions have potential for energy extraction or propulsion device. The propulsion performance of oscillating foil was studied early [6–10]. To study the kinematic, wake structure and flow characteristics of oscillating hydrofoil propulsion, lots of experimental and numerical simulation have been conducted [11,12]. Compared with propulsion of oscillating foil, researchers taken effort to energy extraction performance relatively late.

The concept of oscillating foil energy harvester was initially proposed by McKinney and De Laurier [13], they demonstrated the feasibility of harmonically oscillating foil extracting energy from the oncoming flow. Then, Jones and Platzer analyzed the aerodynamics of flapping foil using unsteady panel code as well as Navier-Stokes simulations [12]. The results revealed that the flow would vary from energy consumption to energy extraction for fixed heaving amplitude and frequency if the value of pitching amplitude is sufficiently high. Further, more systematic computations with fluid software Fluent and experimental investigations using prototype were conducted by Kinsey and Dumas [5,14,15]. The effects of kinematic parameters and geometric parameters were revealed based on the prescribed motion model. Extensive work related to energy harvesting performance of flapping foils can also be obtained in the study by Shimizu et al. [16], Xiao [17], Zhu [18], Campobasso and Drofelnik [19]. Sinusoidal flapping motions were usually applied in their work. The influence of kinematic motion parameters and corresponding flow evolutions were more thoroughly investigated.

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To getting a better energy harvesting performance, the energy harvesting capacity of non-sinusoidal profiles for oscillating foils engaged some researchers' attention. In the numerical study of a flapping foil by Young et al. [20] and Ashraf et al. [21], an alternative non-sinusoidal motion was used for wind and hydropower generator. Xiao et al. used a trapezoidal-like pitching motion combined with a sinusoidal heaving motion to realize a non-sinusoidal profile [22]. Their results demonstrated that non-sinusoidal motion improves the power output and efficiency by around 50% over the tested range of parameters. A comparison between the effects of various non-sinusoidal motions was performed by Lu et al. [23]. They revealed that a suitable combination of non-sinusoidal heaving motions and non-sinusoidal pitching motions could provide the best energy extraction performance. Further, the numerical simulations of Xie et al. found that relatively large oscillating frequency and pitching amplitude should be used for the optimal energy extraction performance [24].

Recently, some researchers concentrated on the semi-activated system which pitching motion is actuated and heaving motion is induced by variations of the hydrodynamic forces [16,25,26]. Isogai et al. first studied the semi-activated system [27]. In their system, the foil is supported elastically in the heaving direction while the pitching oscillation of the whole foil is mechanically driven by an electric motor with a prescribed frequency and amplitude. Using a linearized thin plate model, Zhu and Peng revealed that the mechanism has a positive energy extraction over a large range of mechanical and operational parameters [25]. Further computations using a Navier-Stokes model were carried out by Zhu et al., the results demonstrated that the performance of the semi-activated system is closely related to vorticity control mechanisms, especially in the interaction between the foil and leading edge vortices [26]. Extensive study on semi-activated system has been performed by Teng et al. [28]. To get rid of the complicated control system and simplify the design, Peng and Zhu also proposed a fully passive oscillating foil system through mounting a oscillating foil on a damper and a rotational spring [29].

However, there are rarely numerical simulations available on the vertical axis oscillating hydrofoil motion model in most of the above researches. This study presents a modified model which aims at vertical axis oscillating hydrofoil energy extraction device.

The rest of the study is organized as follows. The motion model and kinematics are presented at first. Following, the governing equations and computational method are described. The validations of mesh independency and computational method are performed. Next, the numerical results are provided. At the end of paper, some conclusions are given.

2. Motion model and kinematics

The conventional oscillating hydrofoil motion model is defined as the hydrofoil experiencing simultaneously a sinusoidal harmonic heaving motion $y(t)$ and a pitching motion $\theta(t)$ under the oncoming flows [13,14], as shown in Fig. 1. This model is appropriate for the horizontal axis device, and the motion components equations are:

$$\begin{cases} y(\mathrm{t}) = y_0 \sin(2\pi ft + \Phi) \\ \theta(t) = \theta_0 \sin(2\pi ft) \end{cases} \tag{1}$$

where y_0 and θ_0 are, respectively, the heaving amplitude and pitching amplitude; c is the foil chord length; d is the foil thickness; f is the oscillation frequency, and it is considered to be dimensionless as the reduced frequency $f^* = fc/U_\infty$; Φ is the heaving-to-pitching phase difference. U_∞ is the freestream velocity. In this study, Φ is kept constant 90°.

Enlightened by the prototypes of Engineering Business Stingray Limited [30] and BioPower Systems Limited [31], this study proposes a modified motion model which is more suitable for vertical axis devices. Fig. 2 shows the modified oscillating hydrofoil motion model. Compared to with Fig. 1(a), the device presented in Fig. 2(a) has a simplicity design. In a shallow water, the upper part of a foil faces higher velocity than that of the lower section. The prototype is more suitable for operation under such conditions [1]. The pitching axis experiences a periodic reciprocating arc motion rotating with the center point (see Fig. 2(b)). Synchronously, the hydrofoil performs a sinusoidal pitching motion around the pitching center. The arc motion is equivalent to the heaving motion of horizontal axis motion model. For comparison purposes, heaving motion is applied to indicate the arc motion for the modified motion model. It can be expressed mathematically as follows:

$$\begin{cases} \theta(t) = \theta_0 \cos 2\,\pi ft \\ x(t) = R\cos[H_0 \sin 2\,\pi ft] \\ y(t) = R\sin[H_0 \sin 2\,\pi ft] \end{cases} \tag{2}$$

$$\begin{cases} V_x(t) = \dfrac{dx(t)}{dt} \\ V_y(t) = \dfrac{dy(t)}{dt} \end{cases} \tag{3}$$

where R is the hydrofoil's motion radius. It represents the length from pitching axis to the heaving axis. For most researches on oscillating foil, the pitching axis is located at 1/3 of the chord length from the leading edge. Therefore, it is a reasonable choice for this study. H_0 is modified model's heaving amplitude; $V_x(t)$ and $V_\mathrm{y}(t)$ are, respectively, the hydrofoil velocity in the x component and y component. The flow loads through a force $F_\mathrm{X}(t)$ parallel to the oncoming flow direction, a force $F_\mathrm{Y}(t)$ perpendicular to the oncoming flow direction, and a moment $M(t)$ about the pitching axis. The corresponding force coefficients $C_\mathrm{X}(t)$, $C_\mathrm{Y}(t)$ and moment coefficient $C_\mathrm{M}(t)$ can be defined as follows:

$$C_X(t) = F_X(t) \bigg/ \frac{1}{2}\rho U_\infty^2 c \tag{4}$$

$$C_Y(t) = F_Y(t) \bigg/ \frac{1}{2}\rho U_\infty^2 c \tag{5}$$

$$C_M(t) = M(t) \bigg/ \frac{1}{2}\rho U_\infty^2 c^2 \tag{6}$$

where ρ is fluid density. The instantaneous power extraction $P(\mathrm{t})$ and the time-averaged power denotes $\overline{P}$ can be expressed as follow.

$$P(t) = F_X(t)\frac{dx(t)}{dt} + F_Y(t)\frac{dy(t)}{dt} + M(t)\frac{d\theta(t)}{dt}. \tag{7}$$

$$\overline{P} = \frac{1}{T}\int_0^T P(t)\mathrm{d}t. \tag{8}$$

We can further define the non-dimensional instantaneous power coefficient $C_\mathrm{P}(t)$ by the sum of the heaving contribution C_PX, C_PY and a pitching contribution C_PM:

$$C_\mathrm{PX} = \frac{2}{\rho U_\infty^3 c} F_X(t)\frac{dx(t)}{dt} \tag{9}$$