Ocean Engineering 153 (2018) 353–362

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Effects of time-varying freestream velocity on energy harvesting using an oscillating foil

Penglei Ma, Yong Wang *, Yudong Xie **, Zhipu Huo

Key Laboratory of High-Efficiency and Clean Mechanical Manufacture, School of Mechanical Engineering, Shandong University, Jinan, Shandong Province, 250061, China

ARTICLE INFO

Keywords:
Tidal energy
Oscillating foil
Time-varying freestream
Energy harvesting
Hydrodynamic

ABSTRACT

The hydrokinetic turbine, using an oscillating foil to extract tidal energy, offers an obvious advantage in shallow water. The software Fluent is used to solve the 2D unsteady incompressible Navier-Stokes equations around an oscillating foil with computations performed with using NACA0015 foil. The parameter μ_x which indicates the oscillation frequency ratio between the freestream and foil motion, is introduced to identify the effects of time-varying freestream velocity. The mean power coefficients are examined over one period and eight periods, the force evolution is reviewed, and the flow fields around foil are analyzed. The results indicate that time-varying freestream velocity leads to fluctuation of the cycle-averaged power coefficient $\overline{C_P}$, with the maximum fluctuation of $\overline{C_P}$ exceeding 16%. A similar variation trend is observed for $\overline{C_P}$ versus μ_x under different motion parameters. Furthermore, it is found that C_{Pmean}, the mean power coefficient over eight periods, fluctuates slightly with μ_x, and the maximum fluctuation of C_{Pmean} is less than 4%. Therefore, the time-varying freestream velocity slightly affects the total energy harvesting efficiency for a lengthy period.

1. Introduction

With an increasing energy demand for human activities, renewable or alternative energy is maintaining a steady progress owing to favorable policies. As an abundant reserve and a clean energy source, tidal energy is also being developed. However, conventional tidal power plants are often gigantic and have a negative effect on the environment. Recently, enlightened by birds and fishes, pioneers McKinney and DeLaurier (1981) proposed the concept of extracting power from wind through an oscillating wing. Compared to traditional turbines based on rotating blades, an oscillating wing is more environmentally friendly (Xiao and Zhu, 2014).

Hydrofoil, which is the critical component of oscillating foil energy harvesting devices, directly affects energy harvesting efficiency and various researchers have focused on its hydrodynamic characteristics, with numerous theories presented and experiments conducted in the past four decades (Xiao and Zhu, 2014; Young et al., 2014). An earlier study was carried out by Jones and Platzer (1997), they studied the transition conditions from propulsion generation to power extracted via an unsteady panel method based on non-linear theory in 1997. Furthermore, Simpson (2009) obtained the sinusoidal effective angle of attack by controlling the foil pitching and heaving motion, and conducted an experiment in a water tank using NACA 0012 foil. His study revealed that parameterizing the oscillating frequency via reduced frequency results in efficiency contours and vortex model alignment between varying flapping amplitudes. Subsequently, further systematic numerical simulations using fluid software CFD methods and prototype experimental investigations have been performed (Kinsey and Dumas, 2012a; Kinsey et al., 2011; Wang et al., 2016).

In order to achieve higher power extraction efficiency, many researchers have paid increased attention to non-sinusoidal motion. Xiao et al. (2012) proposed a non-sinusoidal trajectory profile instead of the conventional sinusoidal heaving/pitching motions. Their results demonstrated that, for different pitching parameters, a larger effective angle of attack always results in higher power extraction and total efficiency. A performance comparison between various non-sinusoidal motions was performed by Lu et al. (2014, 2015) and Xie et al. (2016, 2014). Their results indicated that a suitable combination of non-sinusoidal heaving motions and non-sinusoidal pitching motions provides superior energy extraction performance, and a relatively large oscillating frequency and pitching amplitude should be used for optimal energy extraction performance. Ma et al. (2017) and Karbasian et al. (2016)

* Corresponding author.
** Corresponding author.
E-mail addresses: meywang@sdu.edu.cn (Y. Wang), ydxie@sdu.edu.cn (Y. Xie).

https://doi.org/10.1016/j.oceaneng.2018.01.115
Received 1 April 2017; Received in revised form 26 January 2018; Accepted 31 January 2018

investigated the performance of an oscillating foil with a swing motion. Kinsey and Dumas (2012b), Xu et al. (2016) and Kim et al. (2015) revealed that, compared to using one foil, dual foils with a suitable configuration arrangement exhibit superior energy harvesting performance. Adhering to the prescribed motion model, Zhu and Peng (2009) and Peng and Zhu (2009) proposed a semi-activated system that requires controlling the pitching motion, as well as a self-sustained system that relies on flow-induced unstableness to generate oscillatory motions. Following their study, Deng et al. (2015), Teng et al. (2016), Shehata et al. (2017) and Ma et al. (2018) have invested a great deal of effort on the semi-passive system and fully flow-induced systems.

In comparison with rigid foils, flexible foils (or wings) exhibit superior hydrodynamic performance as well as energy extraction capacity. Recently, a two-dimensional numerical simulation of a flapping foil with local described deformation was performed in order to investigate the advantages of flexibility for energy extraction(Liu et al., 2013; Wang et al., 2016). Tian et al. (2014) studied the effects of passive deformation and active control on the energy extraction capability of a flapping plate. Their results demonstrated that plate flexibility slightly affects the plate power extraction capability, while active control has a significant impact. Using an immersed boundary-lattice Boltzmann method, Wu et al. (2015a; 2015b) studied power extraction from a flapping foil with a rigid or a flexible plate attached to the trailing edge with the prescribed motion model and semi-passive motion. The authors revealed that whether a rigid or flexible tail is utilized could have an obvious effect on the Strouhal number and efficiency of the optimal configuration. Using the same method, Liu et al. (2017) numerically studied flexibility effects on the performance of a flapping foil power generator, at a low Reynolds number of 1100. In order to analyze the flexibility effect, Le and Ko (2015) imposed the described deformations in the chord and span-wise directions onto the hydrofoil surfaces. Throughout the parametric study of the aspect ratio variation, they determined that the 3D effect of chord-wise flexible foil is slightly higher than that of rigid foil.

An obvious limitation of the existing studies regarding oscillating hydrofoil energy generation is that the incoming flow is always deemed uniform and steady. This assumption is an oversimplification because real flows are often unsteady and nonuniform. Using 2D numerical simulation, Zhu (2012) investigated the energy harvesting performance of an oscillating foil in shear flow. Tian et al. (2015) studied the phase difference in orbital flows over flapping foils in propulsion and energy harvesting. Chen et al. (2017) and Zhan et al. (2017) numerically investigated the energy harvesting performance of fully- and semi-activated flapping airfoils under wing gust conditions, respectively.

However, the time-varying velocity of the tidal current has not yet been considered systematically in oscillating foil energy generation. In this study, a sinusoidal oscillation freestream is employed to assess the effects of time-varying freestream velocity.

2. Oscillating foil kinematics parameters

As mentioned previously, there are three oscillating foil types based on energy harvesting systems, in accordance with the actuation mechanisms applied, namely: fully active, semi-active, and fully passive systems (Xiao and Zhu, 2014). With the first type, the foil undergoes the prescribed heaving and pitching motions without consideration of the actuation mechanism. With the second and third types, the foil executes the imposed pitching and induced heaving motions, and the self-sustained pitching and heaving motions, respectively.

For the sake of simplicity, the prescribed motion mode whereby the foil experiences a sinusoidal motion of heaving and pitching simultaneously is used for analysis. In the majority of research on oscillating foil, the pitching axis is located at 1/3 of the chord length from the leading-edge (Xiao and Zhu, 2014); it is therefore a reasonable selection for this study. A sketch of the oscillating foil motion is presented in Fig. 1, and the motion components equations are as follows:

$$\begin{cases} \theta(t) = \theta_0 \sin 2\pi f t \\ y(t) = y_0 \sin(2\pi f t + \varphi) \end{cases}, \tag{1}$$

where c is the chord length; U_∞ is the mean freestream velocity; T is the time of one cycle; θ_0 and y_0 are the oscillating amplitudes for pitching and heaving, respectively; $y_0/c = 1$; f is the oscillation frequency; and φ is the phase difference between the heaving and pitching motions. In the study, φ is kept constant at 90°. The reduced frequency f^* is defined as $f^* = \pi f c/U_\infty$ and the heaving velocity is $V_y(t) = \mathrm{d}y(t)/\mathrm{d}t$.

The tidal current cannot maintain a constant velocity, owing to the seabed conditions and wind wave effects. According to data collected by Engineering Business Limited (DTI, 2005) and Kinsey and Dumas (2012a), the freestream velocity varies over time. For the sake of simplicity and referring to other assumptions (Gharali and Johnson, 2013; Johansen, 1999; Zhan et al., 2017), the freestream velocity is assumed as a sinusoidal varying form, as illustrated in Fig. 1. The horizontal velocity $U(t)$ is governed by

$$\frac{U(t)}{U_\infty} = 1 + \lambda \sin(2\pi f_v t), \tag{2}$$

where λ is the reduced freestream oscillation amplitude and f_v is the freestream oscillation frequency. The freestream oscillation factor μ_x is defined as

$$\mu_x = \frac{f_v}{2f}, \tag{3}$$

where μ_x ranges from 0 to 1. It should be noted that $\mu_x = 0$ represents a constant freestream velocity.

The instantaneous power $P(\mathrm{t})$ extracted from the oncoming flow comes from the sum of the heaving and pitching contribution

$$P(\mathrm{t}) = P_h(t) + P_\theta(t) = F_Y(t)V_y(t) + M(t)\omega(t), \tag{4}$$

where $F_Y(t)$ is the force component in the vertical direction, and $M(t)$ is the torque around the pitching center. The $F_Y(t)$ and $M(t)$ values can be dealt with in a dimensionless manner, as the lift coefficient $C_Y(t)$ and moment coefficient $C_M(t)$, respectively. Furthermore, the power coeffi-

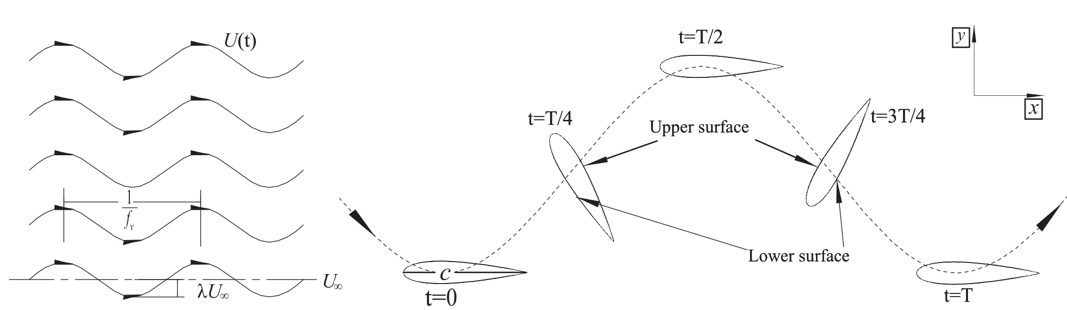

Fig. 1. Schematic of oscillating foil in time-varying freestream.