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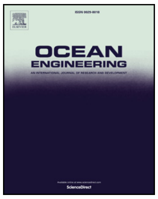

Effects of pitching motion profile on energy harvesting performance of a semi-active flapping foil using immersed boundary method

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ABSTRACT

Effects of pitching motion profile on energy harvesting performance of a semi-active flapping foil are numerically studied using immersed boundary method. Firstly, the numerical method is validated by considering a sinusoidal pitching semi-active flapping foil at Re = 1000 and a uniform flow over a stationary foil at Reynolds number Re = 500. Then, we consider a semi-active flapping foil with Reynolds number Re = 1000 and study the effect of sine-like and cosine-like pitching motion on the energy harvesting performance at reduced frequency $f^* = 0.16$. We study the pitching, with a gradual change from a sinusoid/cosinusoid to a square wave as β is increased from one. We found that increasing the value of β is ineffective to enhance energy harvesting efficiency for sine-like pitching motion, which is in agreement with the results of Deng et al. (2015) and Teng et al. (2016), however, for cosine-like pitching motion, the highest energy harvesting efficiency of 51.81% is recorded for pitching amplitude $\theta_0 = 60^\circ$ and $\beta = 2.0$. Meanwhile, we observed that cosinusoidal pitching motion is more efficient for energy harvesting than sinusoidal pitching motion, and non-cosinusoidal pitching motion can enhance the harvesting efficiency compared to cosinusoidal pitching motion. In detail, we report the different performances of the sine-like and cosine-like pitching motion to study the mechanical mechanism of enhancing energy harvesting efficiency.

1. Introduction

In the new century, the prominent problems of energy sources and environment are more and more severe. Using the renewable and zero-pollution energy such as solar energy, wind energy source and hydro-energy instead of unregenerate energy sources such as coal, natural gas and oil plays an important role in protecting natural environment (Olabi, 2012; Karbasian et al., 2015), improving human's living and developing renewable energy economy (Antonio et al., 2018; Paiva et al., 2018) and so on. As a kind of green energy, solar power technologies have emerged as a sustainable energy solution (Khan and Arsalan, 2016). There are many mature thermal energy storage materials, solar energy conversion and its application methods in solar energy field enable dispatch ability in generation of electricity and home space heating requirements (Alva et al., 2017; Guney, 2016). Wind is the indirect form of solar energy and is caused by differential heating of the earth's surface by the sun. Wind energy exploitation has a long history work on the main issues of global market facts, technology, economics and environmental performance (Kaldellis and Zafirakis, 2011). There are also many advanced wind energy technologies and reliability evaluation models for design, control systems and economics of wind energy conversion system. Many progresses (Islam et al., 2013) were obtained and has been estimated that roughly 10 million MW of energy are continuously available in the earth's wind (Herbert et al., 2007). Although the solar energy and wind energy source are being extensively explored and had been applied in generating electricity, extracting the energy from the ocean through the hydrodynamic machinery is still the most important way to capture energy.

In general, the flow energy harvester with rotating pump-turbines is used for capturing energy from water. As an alternative way to extract power from flowing fluid, flow energy harvester based on a flapping foil is a novel design inspired by aquatic animals, insects and birds, which has become a major focus for renewable energy research. Such a flapping foil turbines promise some key potential advantages, including lower foil velocities (and hence lower noise and wildlife impact (Shao and Pan, 2011)), and more effective small-scale and shallow water operation (Young et al., 2014). Wu (1971), Wu and Chwang (1975) first proposed the concept of extracting flow energy from the unsteady flow fields through an oscillating wing. The application of a flapping foil to extract flow energy from uniform flows was first proposed by Mckinney

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and Delaurier (1981). Lindsey (2002) studied the feasibility of oscillating-wing power generators. Their work suggests that a wing-mill could compete with conventional windmills in generating power. Flow energy harvesters based on flapping foils are investigated by many researchers as prescribed by reviews (Young et al., 2014; Xiao and Zhu, 2014).

Usually, the device of a flapping foil used for energy harvesting undergoes heaving motion $h(t)$ and pitching motion $\theta(t)$. According to the activating mechanism of the device, the energy converters can be classified into three categories, which are active system, semi-active system and passive system respectively. The performance of an energy harvester depends on foil kinematics (models, frequencies, amplitudes and time histories of motion), foil and system geometry (shape, configuration and structural flexibility) and flow physics effects (Reynolds number and turbulence, shear flows and ground effect).

For fully-active system, the heaving motion $h(t)$ and the pitching motion $\theta(t)$ are prescribed, the models are simple and easy to formulate mathematically, the results obtained can provide some useful theoretical insights and guidance for real devices design. Many extensive works have been carried out on fully-active systems (Jones and Platzer, 1997; Dumas and Kinsey, 2006). Kinsey and Dumas (2008, 2011) studied the power-extraction efficiency of a single oscillating airfoil with different reduced frequency and different pitching amplitude, in which the efficiency reached as high as 35%. Esfahani et al. (2015) and Karbasian and Kim (2016) have found that the motion trajectory of flapping foil would influence the flowing structure and change the vortex shedding pattern and wake zone behind the airfoil. Zhu (2011) reported that the energy harvesting efficiency of a flapping foil is related to the stability of the wake behind it. Karbasian et al., (2016) have considered the effect of swill arm length on the performance of flapping foil hydrokinetic turbine and the amount of power. The found that the swill arm mode may increase the amount of extracted power and improve the performance of hydrokinetic turbine. Non-sinusoidal oscillating motions have also been introduced to enhance the efficiency of energy harvesting system. Xiao et al. (2012) adopted a trapezoidal-like pitching motion, they found that there exists an optimal pitching motion which was proved to dramatically increase the output power coefficient and total output efficiency as high as 63% and 50%. Lu et al. (2014) studied the effects of different non-sinusoidal motion on the flapping foil energy extraction performance. They found that energy extraction performance can be significantly improved with an appropriate combination of non-sinusoidal pitching and non-sinusoidal plunging motion. Moreover, Karbasian et al. (2015) investigated the power extraction possibility by a number of flapping hydrofoils in tandem formation. They have obtained higher power efficiency at low Reynolds number and flapping frequency.

The fully-active system need input much power since both the heaving motion $h(t)$ and the pitching motion $\theta(t)$ are all actuated by extern electricity. Therefore, some researcher put their eyes on the study of the semi-active system, in which only need to control/actuated the pitching motion $\theta(t)$. The pitching motion is activated by input energy and energy harvesting is achieved through the resulting heaving motion generated by fluid dynamic lifting force. We extract positive net energy if the energy harvesting is higher than energy input. The performance of a semi-active flapping foil energy harvester has been numerical investigated by Zhu and Peng (2009) and experimental researched by Cochard et al. (2012). They suggested that the performance depended on mechanical parameters including the magnitude of the damping and the location of the pitching axis, as well as operational parameters, e.g. the pitching frequency and pitching amplitude. Deng et al. (2015) studied the effects of efficiency enhancement by sinusoidal motion for different reduced frequency f^* and pitching amplitude θ_0. They identified the optimal combination of the parameters of pitching amplitude $\theta_0 = 75^\circ$ and reduced frequency $f^* = 0.16$, which obtained the highest total energy efficiency more than 33%. Teng et al. (2016) also researched the effects of efficiency enhancement by non-sinusoidal motion for different reduced frequency f^* and different adjustable parameter β, one can gradually change the designed pitching profile from sinusoidal ($\beta = 1.0$) to a square wave ($\beta \to \infty$). They also pointed out that the optimal combination of the parameters is pitching amplitude $\theta_0 = 75^\circ$ and reduced frequency $f^* = 0.16$, with the highest total energy efficiency of 32%. Moreover, they found that the increasing of β is ineffective in semi-active system when θ_0 and f^* approaching its optimal value. As pointed out by Teng et al. (2016) that the increasing effect of non-sinusoidal pitching amplitude on efficiency was weak as θ_0 approaching its optimal value.

Compared to semi-active system, passive system is more simplified on mechanical design, in which the oscillatory motion in heaving and pitching directions are all actuated by the flow-induced instabilities. The subsequent energy extraction is positive since no actuation system is needed. Peng and Zhu (2009) examined a fully passive flapping foil system by mounting a flapping foil on a damper and a rotational spring. Four different responses were recorded, and stable energy could be obtained when periodic pitching and heaving motion were both periodically excited. Zhu (2012) also investigated the response of a purely passive flapping foil flow energy harvester in a linear shear flow. It was indicated that in shear flows the devices were still capable of undergoing periodic responses as in uniform flows, which was essential for reliable energy harvesting. Wang et al. (2017) numerically investigated the structural response and energy extraction of a foil undergoing two-degree-of-freedom fully passive flapping motions in a two-dimensional flow at $Re = 400$. In the parametric space of flow reduced velocity and pivot location investigated, five response regimes and the highest cycle-averaged power efficiency 32% are identified. Young et al. (2013) studied a fully passive flapping foil, declaring an efficiency as high as 41%. Also, some literature regard that structure flexibility may have significant effect on the energy harvesting performance (Tian et al., 2014; Wu et al., 2015a; b; Liu et al., 2017).

As described above, extensive work has been researched on fully-active system and obtained the highest energy harvesting efficiency of 50% in according to the study (Xiao et al., 2012). However, only a few of work has been studied on fully-passive system and semi-active system, with the highest energy harvesting efficiency of 41% and 33%, respectively. Inspired by the study (Xiao et al., 2012), we are interested in combining the prescribed cosine-like pitching motion with heaving motion determined by unsteady hydrodynamic forcing on the foil can enhance the energy harvesting efficiency or not. Therefore, in the present work, we employed numerical code based on projected immersed boundary method to solve the two-dimensional Navier-Stokes equations. The flow by a semi-active flapping foil is simulated with prescribed sinusoidal, non-sinusoidal, cosinusoidal and non-cosinusoidal pitching trajectories, while the heaving motion is determined by the hydrodynamic force acting on the foil. By tuning an adjustable parameter β, one can gradually change the designed pitching profile from sinusoid/cosine-profile ($\beta = 1.0$) to a square wave ($\beta \to \infty$). This study is therefore concerned on the difference of how motion trajectory affects power extraction performance. We consider a two-dimensional NACA0012 oscillating foil, with the Reynolds number of 1000 calculated by the incoming flow velocity, the chord length and the properties of the fluid. Computations will be simulated for a sinusoidal pitching trajectory with a series of β values along with pitching amplitude $\theta_0 = 75^\circ$ and reduced frequency $f^* = 0.16$. Another pitching trajectory is computed with a series of β values along with different pitching amplitudes (θ_0) and reduced frequency $f^* = 0.16$.

The rest of this paper is organized as follows: the governing equations and the basic steps of the solution will be simply described in section 2. Then the validation of the PIBM is shown in section 3. In section 4, the numerical results of sine-like and cosine-like pitching motions for flapping foil are discussed and compared. Finally, the paper is concluded by closing remarks in section 5.