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The power extraction by flapping foil hydrokinetic turbine in swing arm mode

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ABSTRACT

In the present study the power extraction capability by flapping foil hydrokinetic turbine is investigated. The heaving motion of the foil is considered in two different motion patterns including the simple linear translational motion and the rotation of swing arm on which the foil is mounted. The laminar and incompressible flow around a NACA0012 foil is conducted using Computational Fluid Dynamics (CFD) method. It is shown that the power extraction is possible and more desirable in the lower reduced frequencies. Additionally, the swing arm mode may increase the amount of extracted power and improve the performance of hydrokinetic turbine. Changes in kinematics of flapping foil alter the angle of attack profile and the local Reynolds number on the surface of the foil. These two sensitive changes influence on the sub-layer flow near to surface of the foil and make the vortex structure to be complex during flapping cycle. In the other words, in swing arm mode the vortex creation, growth, separation and shedding occur with an alternative pattern compared to simple mode. Finally, it is shown that the importance of the swing arm mode is in a certain range of swing arm lengths.

1. Introduction

The development of systems to extract power from renewable energy resources becomes a great challenge in recent decades. The rise of energy consumption in association with population growth and other destructive environmental effects may responsible for these variations in energy policy. The renewable energies enable to give us free power without any notable constructive effects. The power extraction from wind and tidal currents can be considered as the promising energy resources among the other natural resources due to their energy capability and availability [1]. The estimated power generated by the movement of earth's atmosphere is around hundreds of terawatts [2] which caused to rapid growth of wind power industry. The power extraction from wind and tidal currents is generally obtained by means of turbines with rotating blades [3,4]. On the point of other utilized mechanism to extract power, the flapping foil also enables to harness power from free surface waves, open channels and uniform streams [5,6]. The application of flapping foil is inspired from the ability of animals whom extract energy during their locomotion [7] due to their excellent hydrodynamic or aerodynamic maneuverability in flow. The flapping foil ability in thrust generation scheme has been examined by many researchers [8–15], while power extraction scheme has been paid attention since recent years [16–25].

Fernandes and Armandei [26] also investigated thoroughly on oscillation-based scheme for power extraction from ocean currents. They innovated a novel model with interesting advantages and it can be classified as new model of turbines named Vertical Axis Autorotation Current Turbine (VAACT) [27]. The VAACT is a one degree of freedom plate which uses the autorotation phenomenon to rotate around its vertical axis in water current. The state of the art on this turbine is application of the extra moment of inertia and also flapped shape of the rotor blade for improving the autorotation characteristics as the principle of operation of the oscillation-based turbine [28]. On the point of foil-shaped model, The flapping foil power extraction was initially considered by McKinney and Delaurier [6] and they realized that the extracted power by the flapping foil have a comparable power efficiency relative to that of rotational turbines. According to experimental and numerical studies, Kinsey and Dumas [20] reported that the motion

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parameters have the strong effect on the hydrofoil performance. Zhu and Peng [22,25] used Computational Fluid dynamics (CFD) method based on the Navier–Stokes solver. They realized that the positive net energy can be achievable only in low flapping frequency. Kinsey et al. [29] used flapping foil hydrokinetic turbine to harvest power from water currents. They reported the best power efficiency of 40% with considering mechanical losses in power system. Karbasian et al. [30] also studied the possibility of power extraction for by flapping foil in tandem arrangement and they noticed that it is possible to increase performance of flapping foil systems using multi-stage foils arranged in tandem form. This shows the hydrokinetic flapping foil can contest in energy extraction with the modern rotor blades hydro turbines. To gain high efficiency in conventional rotor blade turbines the flow is preferred to keep smoothly attached to blades surface [31], while the flapping foil can generate higher instantaneous forces when the flow is separated from surface of the blade. Energy production from tidal streams is very promising due to the high energy density of water and its good predictability [2]. The flow speed for commercial application of tidal stream turbines is currently considered between 2.5 and 3.2 m/s [24]. Furthermore, the flapping foil hydrokinetic turbine can generate power with high efficiency even in lower stream velocity such as 1.8 m/s, which can double the number of usable tidal current sites around the world [32]. This type of turbines can operate in low speed currents and flapping frequencies with the high level of power efficiency, which may reduce destructive environmental impacts. The rotary hydrokinetic turbines have the large wake zone which may alter shear stress imposed on the sea bed and influence strongly on the sediment transport and scour processes [33]. Fig. 1 is provided in order to illustrate schematically the mechanism of conventional flapping foil hydrokinetic turbines (Fig. 1). Two flat blades move harmonically in heaving motion direction (up and down) normal to free stream velocity. The system is implemented on pile which is inside of the sea bed. The blades have also pitch motion around a shaft located between blades and power storage device (e.g. fly wheel).

As mentioned above, the flapping foil hydrokinetic turbines for harnessing the flow power use a heaving motion coupled with a pitching motion of the foil about a pivot point. In design of these type of turbines the conventional heaving motion is the pure translation one [31], while in other configuration the heaving motion is rotation of a swing-arm on which the foil is mounted. The company BioPower System [30,34] in Australia is developing “BioSTREAM” system which incorporates a single foil mounted on a swinging arm [35–37] to harness power from tidal currents. The UK company Pulse Tidal [38] has been also developed “Pulse-Stream 100” and used this type of heaving motion in its design. Furthermore, this type of configuration have been thoroughly studied by Kinsey et al. [29] and Platzer et al. [39].

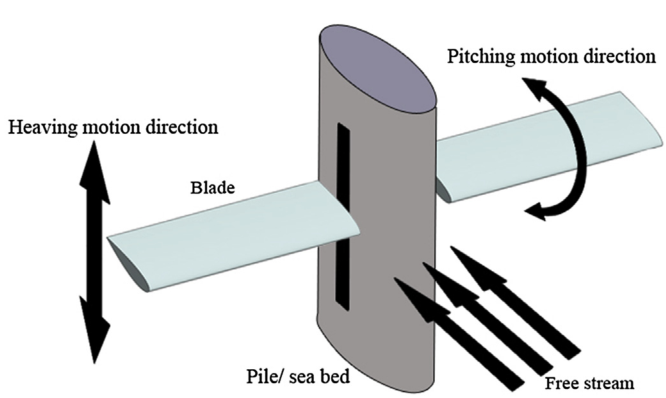

Fig. 1. Schematically diagram of a conventional flapping foil hydrokinetic turbine.

Until recently different strategies have been considered by many researches to improve the performance of flapping foil hydrokinetic turbines and keep its high level of power efficiency during the power generation. Ashraf et al. [17] used an alternative non-sinusoidal foil motion, in which the foil plunge was maintained in a high velocity and followed by fast pitching reversal. They reported that the generated power increases around 17%. Xiao et al. [24] considered motion trajectory of foil during power extraction and they found that a significant increment of output power will be obtained for trapezoidal-like pitching motion over a certain range of Strouhal number. Lu et al. [7] considered different nonsinusoidal heaving and pitching motions and combination of them to improve the output power by this method. Xie et al. [1] also used a modified flapping motion and they reported that the relatively high flapping frequency and low pitching amplitude should be chosen for the most power extraction. Young et al. [40] simulated numerically the fully passive flapping foil power generation and they found that the improving of the energy extraction from flow can be achievable by controlling of formation and location of the leading edge vortex at crucial times during flapping cycle, and interaction of the vortex with the trailing edge. These current studies show the importance of the flapping foil hydrokinetic turbines and its potential to have an improved design for better energy extraction. However, no attention was paid to the effect of swing arm length on the performance of this type of turbine.

The purpose of this paper is to consider the effect of swing arm length on the performance of flapping foil hydrokinetic turbine and amount of power can be extracted. The laminar and incompressible flow around a NACA0012 foil is simulated using CFD method. The dynamic mesh technique is also utilized to model the motion of flapping foil in two different motion patterns including the simple linear translational motion and rotation of swing arm on which the foil is mounted. Based on the introduced motion patterns the performance of the hydrokinetic turbine is predicted and the appropriate range of swing arm lengths is also presented.

2. Physical model

2.1. Solver

In this study, the simulations are performed based on the solving Navier–Stokes (N–S) equations. Using N–S equations, it is possible to obtain some of the major flow features qualitatively, such as development of the leading edge vortex and hysteresis loop of dynamic loading for a hydrofoil encountered with flapping motion [41]. In this simulation the flow is considered two dimensional, laminar and incompressible. The numerical simulation is also carried out using Open Foam [42]. The governing equations for the flow field with remarked specifications around a NACA0012 foil are expressed as follows:

$$\nabla \cdot V_i = 0 \tag{1}$$

$$\left(\frac{k}{\pi}\right)\frac{\partial V_i}{\partial \tau} + (V_i \cdot \nabla)V_i = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2 V_i \tag{2}$$

In these equations $i = 1$ and 2 indicate the x and y coordinate, respectively. V_i is the velocity of fluid in i direction ($V = (u,v)$), $\tau = t/T$ (T is flapping period) and $p = \text{pressure}/\rho U^2$ (U is free stream velocity). Re is Reynolds number, which is defined as follows:

$$\mathrm{Re} = \frac{\rho U c}{\mu} \tag{3}$$

where ρ, c and μ are fluid density, chord length and viscosity,