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Simulation of power extraction from tidal currents by flapping foil hydrokinetic turbines in tandem formation

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A B S T R A C T

In the present study the power extraction possibility by a number of flapping hydrofoils in tandem formation is investigated. A code is developed to predict power extraction capacity for the various number of flapping hydrofoils based on the kinematic and hydrodynamic models. The selected hydrodynamic model follows two dimensional quasi-steady hydrodynamic instability formulation. It is shown that the power extraction is also possible from water stream with the low Reynolds number. As a result of power extraction at low speed flows, the predicted maximum power efficiency is also in lower flapping frequencies. Furthermore, it is found that there are limited number of required flapping hydrofoils in tandem formation, in which the power influence rate drops notably after the second flapping hydrofoil. The flapping hydrofoils at downstream also experience higher hydrodynamic forces, while the flapping hydrofoil kinematics is the key parameter to harness extracted power. As a result of this investigation, the introduced model and code can be used as one of initial tools to predict power capacity for obtaining vast concept regarding tidal sites with the flapping foil hydrokinetic turbines.

1. Introduction

The rise of energy consumption with population growth, fuel prices, and greenhouse effect concerning motivate development of power extraction system from renewable energy resources. The renewable energies enable to give us free power without any notable constructive effects. Among the renewable energy originated from natural resources (hydro, sunlight, tides and so on) power extraction from wind and tidal currents attracted many scientists due to their promising energy capability and availability [1]. The estimated power generated by the movement of earth's atmosphere is around hundreds of terawatts [2] which led to rapid growth of wind power industry. This power extraction is generally obtained using turbines with rotating blades [3,4]. However, the flapping foil also enables to harness power from free surface waves, open channel and uniform streams [5]. Application of flapping foil is inspired from ability of animals that show excellent hydrodynamic or aerodynamic maneuverability by flow energy extraction during their locomotion, such as birds or fishes [6]. The ability of flapping foil in thrust generation scheme has been studied by many researchers due to its great and exclusive aero/hydrodynamic performance [7–11], while power extraction scheme has attracted attention since recent years [12–21]. The concept of flapping foil power extraction was initially considered by McKinney and Delaurier [5] and they found that the harnessed power by flapping foil has a comparable power efficiency relative to that of rotational turbines. Kinsey and Dumas [16] also performed experimental and numerical studies on energy extraction by flapping foil and they also reported that the motion parameters have strong effect on hydrofoil performance. Furthermore, some researchers studied energy extraction by flapping foil with actuated power. Zhu and Peng [18,21] used fluid-structure interaction based on the Navier–Stokes solver and they found the positive net energy only at low flapping frequency. Simpson et al. [22] performed experimental setup to measure harnessed power by flapping foil and they announced that power efficiency of around 43% would be achievable with simple sinusoidal flapping motion. Kinsey et al. [23] utilized flapping foil hydrokinetic turbine to harvest power from water currents. They reported the best power efficiency of 40% once the overall losses in mechanical system were taken into account.

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According to results of Simpson et al. [22] and Kinsey et al. [23] it is realized that hydrokinetic flapping foil can contest in energy extraction with modern rotor blades hydro turbines.

In order to show why bio-inspired mechanism have attracted many attentions in energy extraction some descriptions are provided. To obtain the high efficiency in conventional rotor blade turbines the flow is preferred to keep smoothly attached to blades surface [24]. In contrast, the flapping foil can generate higher instantaneous forces, while the flow is separated from blade surface. This separated flow causes to form low pressure leading edge vortex, which exerts high pressure force around the foil leading to higher lift force. Energy production from tidal streams is very promising due to high energy density of water and its good predictability [2]. The flow speed for commercial application of tidal stream turbines and wind turbines are currently considered 2.5–3.2 m/s [20] and 5–10 m/s [25], respectively. On the other hand, according to theoretical maximum power efficiency of 59% by Betz criterion [26], the rotor blade turbines enable to approach 45% at their limited optimum condition. Flapping foil hydrokinetic turbine can generate power with this level power efficiency even with lower stream velocity such as 1.8 m/s, which can double the number of usable tidal current sites around the world [27].

On the point of hydrokinetic turbine effect on aquatic environment, turbulence induced by these type of turbines can potentially impact aquatic habitats [28]. With increasing of wake in turbulence, the flow may alter shear stress imposed on the river or sea bed which could strongly influence on sediment transport and scour processes [28]. As the flapping hydrofoil can operate at lower speeds and flapping frequencies with the high level of power efficiency, it may reduce destructive environmental impacts and prevents from harms to aquatic habitats.

Fig. 1 shows schematically an arbitrary river cross section selected for hydrokinetic turbines operation. According to Fig. 1 (a) the two rotary blade turbines can be used based on the river characteristics. Fig. 1 (b) displays binary flapping hydrofoils implemented at the same river cross section. As it is shown, the swept area for rotary blade turbines allocates two circular areas which causes to be useless most of the river cross sectional area. On the other hand, the flapping hydrofoil turbine assigns a rectangular swept area which covers most of river cross sectional area.

The flapping hydrofoil in tandem formation can increase the power efficiency. On the other hands, these types of hydrokinetic turbines can get accustomed with aquatic environment due to its significant and positive characteristics. Lehmann [17], Jones et al. [15] and Akhtar et al. [12] demonstrated that the amount of harvested power can be increased by means of two flapping foils in tandem arrangement, at which the downstream foil recover power from wake of upstream foil. Recently, all investigations into flapping hydrofoil power extraction were done based on the one or two hydrofoils, but the capability of power extraction by multiple flapping foils have not yet considered.

In this study, the power extraction ability by a series of flapping foils in tandem formation is numerically considered based on the introduced model. In this model all hydrofoils are considered to have sufficient distances in order to put down wake effect on downstream hydrofoils. In this model set of nonlinear equations, which are associated with quasi-steady hydrodynamic model [29] are solved to predict hydrodynamic forces and power efficiency. Employing this model, makes it possible to predict ideally how many flapping hydrofoil in tandem formation will be needed to extract power from water stream. Additionally, the introduced procedure in this paper can be used as a simple and initial tool to estimate power extraction capacity in investments required for implementing tidal sites with flapping foil hydrokinetic turbines.

2. Physical model

In this section the power extraction using some of flapping hydrofoils located in tandem arrangement is considered. For better understanding, consider an open channel with large length (Fig. 2). The free stream velocity enters to channel and then exhaust from downstream. By passing of water from this channel the series flapping hydrofoils capture the fluid energy and lead to decrease fluid velocity. On the other hand, according to mass conservation law, reduction in velocity causes to increase the height of water level in channel. This phenomenon causes some of water exit from channel and then the water level reach again to its previous one. In open channel, the water level always will be constant while the fluid velocity decreases along the channel. The reason that an open channel is selected for flapping hydrofoil consideration, is that the river or any flow stream like that can be divided into channels with flapping hydrofoil series. This procedure makes it possible to prevent from the entrance of any solid subjects which may provide serious damage for hydrofoils. Furthermore, it will be able to control water flow.

Fig. 3 shows schematic of a flapping hydrofoil which is located in the direction of free stream velocity, U_1. The plunge motion of hydrofoil is defined by $h(t)$ and its pitch motion is denoted by $\theta(t)$. The maximum distance between hydrofoil shaft and plunge motion

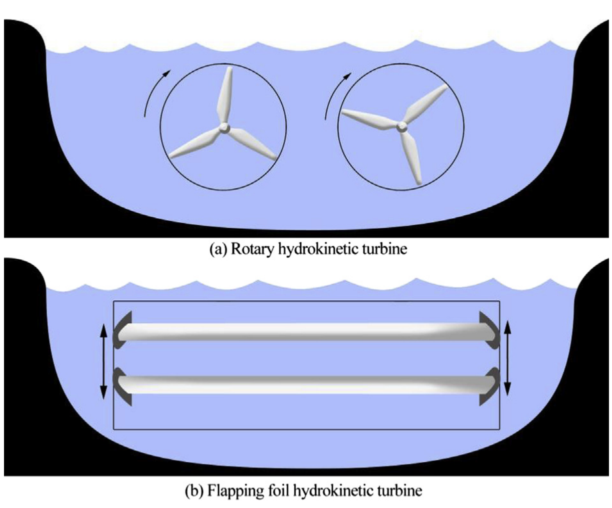

Fig. 1. Schematically diagram of river with two different hydrokinetic turbines for power extraction from water stream: (a) Rotary turbine with two circular swept areas; (b) Flapping hydrofoil turbine with rectangular swept area.

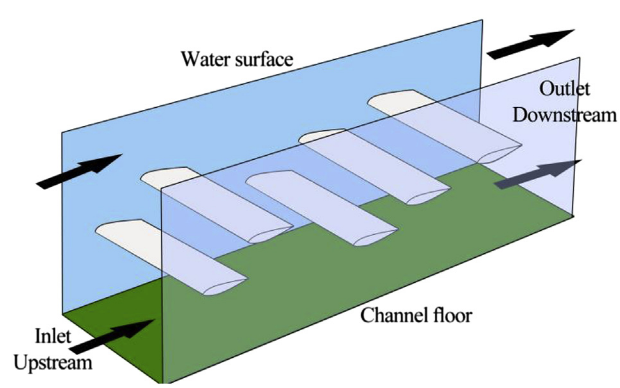

Fig. 2. Schematically diagram of an open water channel at which the flapping hydrofoils are arranged in tandem formation.