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Numerical investigation on energy extraction of flapping hydrofoils with different series foil shapes

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ABSTRACT

As a new mode of energy extraction, flapping foils show broad application prospects. How to improve the energy extraction efficiency (η) of wind or hydro energy with flapping foils has become a focused issue for scientists in this field. This paper numerically investigated the energy extraction of flapping hydrofoil with different NACA 4 and NACA 6 series foil shapes. Firstly, compared with experimental results, the simulation results were validated. Secondly, by adopting different series of foil shapes, simulation was conducted for energy extraction of flapping foils which were moving harmonically in current: ① symmetric foils with different maximum thicknesses; ② symmetric foils with different maximum thickness positions; ③non-symmetric foils with same maximum thickness, maximum thickness position and camber, but different maximum camber positions; ④ non-symmetric foils with same maximum thickness, maximum thickness position and camber position, but different maximum cambers. It is found that for symmetric foils with different maximum thicknesses, η basically increases first and then decreases with the increase of maximum thickness; for symmetric foils with different maximum thickness positions, η first increases and then decreases when maximum thickness position moves from the leading edge to the trailing edge; for non-symmetric foils with same thickness, η shows lower value with larger camber; compared with maximum camber position, the maximum thickness shows larger influence on η.

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1. Introduction

With the rapid economic development, energy demand for human continues to increase. With large exploitation and utilization of energy resource, especially non-renewable fossil fuels, the contradiction between energy and environment has become increasingly intensifying [1]. In order to protect the environment, the development of renewable energy including wind energy and hydro energy (river, ocean current and tide) has attracted extensive attention from all over the world. Wind power is resource-rich, widely distributed, clean, and it extracts kinetic energy from the wind and converts it into a useful type of energy: thermal, mechanical, or electrical. However, although the frequency and intensity of wind can be sometimes estimated, it is still not really very predictable by climatic fluctuations which can create challenges for the balancing of the transmission system. By contrast, tidal power is predictable besides being clean, renewable and reliable [2]. There are mainly three types of tidal power including wave energy converters, tidal lagoons and tidal barrages and tidal current. Turbines used in tidal current showing a similar way to make use of air movement, and it presents lower cost and visual impact, and environmental friendly. As a clean and renewable energy, tidal current power has become one of the most promising alternative energy sources.

A traditional way to utilize tidal energy is to obtain kinetic energy of flowing water through a rotary turbine, while animals such as aquatic animals, insects and birds utilize oscillatory motions with fins or wings to produce highly effective propulsive and maneuvering forces [3]. For tidal current energy conversion devices with oscillating hydrofoil, a way accessing to clean energy by adopting bionic flapping foil has become a new method to obtain clean energy. Fig. 1 shows an example for flapping hydrofoil set in shallow water to exact energy. By simply extending the hydrofoil

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Fig. 1. Examples for flapping hydrofoil (left) and rotary turbine (right) set in shallow water to exact energy.

span, the rated power will increase accordingly. It is easier to produce flapping hydrofoil system due to its simple geometry compared with rotor blade system. The flapping foil system can be installed in shallow water since their sweeping windows are rectangular. Besides, this system shows no threat to aquatic animals and is easier to be manufactured compared to traditional rotary turbines [4]. Flapping foil which is a new mode for energy extraction has become a useful complement to the existing horizontal and vertical wind energy utilization device. How to improve the energy extraction efficiency for wind or hydro energy has become a very meaningful research subject.

Researchers experimentally investigated the energy extraction for flapping foils [5–7]. McKinney [5] at first experimentally investigated a windmill to extract wind energy by utilizing a harmonically oscillating wing. A theoretical analysis was developed by using unsteady-wing aerodynamics from aeroelasticity. It was found that experiment compared favorably with theory which proved the capability of the windmill to extract energy compared with rotary designs. Inspired from fish to extract energy from unsteady flows and vortical structures, Simpson [6] experimentally studied the foils with both sinusoidal sway (heave) and yaw (pitch) motion. At Reynolds numbers 13800, NACA 0012 foils with aspect ratios of 4.1, 5.9 and 7.9 were tested, and parameters including yaw amplitude, Strouhal number and phase angle between sway and yaw were also investigated. With simple sinusoidal motions, efficiencies can reach up to 43 ± 3%. Kinsey [7] conducted prototype testing of a hydrokinetic turbine for oscillating hydrofoils. Through field tests, very encouraging hydrodynamic efficiencies which agreed well with the theoretical predictions obtained in the design phase were presented. An experimental 2kW prototype with two rectangular oscillating hydrofoils of aspect ratio 7 in a tandem spatial configuration were designed, built and tested. Compared with modern rotor blades turbines, this first prototype exceeded expectation and the hydrodynamic efficiency reached about 40%. The research outcomes validated that the oscillating hydrofoils technology is a promising and effective way to extract power from an incoming water flow.

Numerical investigations were also conducted for energy extraction of flapping foils [8,9]. Kinsey [8] conducted parametric study of a single oscillating NACA 0015 airfoil at a Reynolds number of $Re = 1100$ in a power-extraction regime. The frequency and pitching amplitude domain was $0<fc/U_\infty<0.25$ and $0<\theta_0<90^\circ$ with a heaving amplitude of one chord. The highest efficiency of 34% was observed, and the influence of parameters such as heaving amplitude, frequency, geometry and viscous parameters on airfoil performance was discussed. Kinsey [9] also used URANS numerical simulations to study the performance of oscillating hydrofoils. The numerical predictions were validated with experimental results from two rectangular oscillating hydrofoils in a tandem spatial configuration. It was found that the power-extraction efficiency were little sensitive to perturbations in the foil kinematics and upstream velocity. Furthermore, it was proposed that the underestimation of the mechanical losses in the experimental data caused the over-prediction of simulation results for cases of tandem hydrofoils with high frequency.

Studies of energy extraction were conducted for different arrangement of flapping hydrofoils. Karbasian [10] numerically investigated the power extraction for a number of flapping hydrofoils in tandem formation. For limited number of required flapping hydrofoils in tandem formation, the power influence rate dropped notably after the second flapping hydrofoil. Furthermore, higher hydrodynamic force was observed for flapping hydrofoils at downstream, while the flapping hydrofoil kinematics was the key parameter to harness extracted power. In order to maximize the power extraction efficiency of the turbine, Kinsey [11] numerically studied the spatial configuration for two oscillating foils within a hydrokinetic turbine. Tandem spatial configurations were considered and the focus is on the relative positioning of the downstream foil oscillating in the wake shed by the upstream hydrofoil. Unexpectedly high power-extraction efficiencies may be caused by interactions between the downstream foil and the wake vortices, while the downstream foil to contribute negatively to the total power extracted may be caused by unfavorable interaction.

Modified flapping foil geometries based on conventional design were developed [12–15]. Wu [12] studied the power extraction by flapping foil hydrokinetic turbine in swing arm mode. The simulation results showed that the swing arm mode may increase the amount of extracted power and improve the performance of hydrokinetic turbine. Moreover, compared to simple mode in swing arm mode, the vortex creation, growth, separation and shedding occurred with an alternative pattern. Besides, in a certain range of swing arm lengths, the importance of the swing arm mode was showed. Wu [13] attached a flat plate to the trailing edge of the foil to model a flexible tail on a semi-activated flapping foil system. The effects of the mass and flexibility of the tail as well as the frequency of pitching motion on the net power extraction were systematically examined. Based on the numerical result, it was indicated that a deformable tail helped to increase the lift force which directly caused the power extraction enhancement compared with a rigid tail. Additionally, a flexible tail with high flexibility was recommended in the semi-activated flapping foil due to high enhancement of power extraction. Zhu [14] conducted research on energy extraction characteristics of an adaptive deformation oscillating-wing. The proposed oscillating foil can be deformed into a cambered foil to reach higher heave force compared with conventional symmetric foil. The simulation results showed that the proposed oscillating foil with deformation can be about 16.1% higher than the conventional foil. Hoke [15] also studied the effects of time-varying camber deformation on flapping foil power extraction. The vortex interactions showed strong influence on power extraction of semi-passive cases. Besides, the flapping frequency can be significantly altered by the resulting forces and moments.

However, systematic analysis for influence of maximum thickness, maximum camber, maximum thickness position and maximum camber position on energy extraction of flapping hydrofoils hasn't been developed yet. By applying UCFD (Unified Computational Fluid Dynamics) software developed by our research group and using dynamic grid technology combined with motion laws of oscillating hydrofoils, this paper establishes a numerical calculation model for flapping hydrofoils. Through numerical simulation, the force from fluid acting on different series of flapping hydrofoils as well as the interaction between vortex and flapping hydrofoil are analyzed. This paper discusses the relationship between energy extraction efficiencies and maximum thickness, maximum camber, maximum thickness position and

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