Renewable Energy 63 (2014) 550–557

Contents lists available at ScienceDirect

Renewable Energy

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

Investigation on energy extraction performance of an oscillating foil with modified flapping motion

Yonghui Xie [a], Kun Lu [a], Di Zhang [b,*]

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, China
[b] Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, China

ARTICLE INFO

Article history:
Received 11 December 2012
Accepted 14 October 2013
Available online 30 October 2013

Keywords:
Oscillating foil
Energy extraction
Modified flapping motion

ABSTRACT

A modified flapping motion for an oscillating foil is proposed for energy extraction and the energy extraction performance of this proposed motion is numerically studied. Computations are performed at Re = 10^4 with a 2-D elliptical foil with thickness of 10% chord applied. The investigation is undertaken over a wide range of kinematic parameters (reduced frequency k, pitching amplitude θ_0). The results reveal that the power extracted from the oncoming flow mainly comes from the plunging motion and the pitching contribution is quite limited. Detailed examination of motion parameters indicates that at a fixed θ_0 the output power increases with k at first and then decreases with the further increasing k. A similar trend for the variation of output power with θ_0 at a fixed k is also observed. By affecting the effective angle of attack profile, the motion parameters notably influence the development of leading edge vortices and variation of lift force. A mapping of power-extraction efficiency for the oscillating foil in the frequency and pitching amplitude domain is presented. It is found that high k together with low θ_0 is beneficial to energy extraction. For the best energy extraction performance, relatively high k and low θ_0 should be chosen.

1. Introduction

The continuous rise of world energy consumption and the growing commitment of the international community to limit greenhouse effect motivate the development of alternative power extraction systems from renewable sources. Among the renewable energy originated from natural resources such as wave, sunlight, hydro and tides, power extraction from wind or tidal energy is an attractive alternative method. This extraction is generally achieved through turbine-based devices containing rotating blades [1,2]. However, one promising concept in the fields of wind turbines and tidal energy systems relies on the application of oscillating foils as power-extraction devices.

The investigation into flapping foil aerodynamics oscillating foil for thrust generation has been studied by a number of researchers. Only in recent years the energy extraction mechanism of the flapping foil has gradually attracted attention [3–15]. The concept on the energy extraction behavior of an oscillating foil was initially proposed by McKinney and DeLaurier [3] in 1981. They examined the feasibility of wind energy extraction through a combined pitching and plunging foil using analytical and experimental methods. It is found that the output power can be achieved and the efficiency is comparable to that of the rotational wind turbine. Further, Jones and Platzer [4] investigated the flapping foil aerodynamics with unsteady panel code and Navier–Stokes simulations used. The results reveal that if the pitching amplitude was increased to a sufficiently high value, the flow would change from energy consumption to power extraction at fixed plunging amplitude and frequency. Further, Kinsey and Dumas [5] also studied the boundary between energy consumption and power extraction regimes for flapping foil. The power-extraction efficiency as a function of the pitching amplitude and frequency for an oscillating NACA0015 foil was mapped, and it is reported that motion parameters have much stronger effects on foil performances than geometry and viscous parameters. Furthermore, Akhtar et al. [6] and Lehmann [7] demonstrated that by using two foils in tandem formation, the amount of harvested energy could be increased. In this way the downstream foil could recover energy from the wake of the upstream foil. Recently, some researchers investigated the flapping foil for energy extraction with the actuated power required for activating the device considered. Zhu and Peng [8,9] examined

* Corresponding author. Tel./fax: +86 29 82664443.
E-mail addresses: yhxie@mail.xjtu.edu.cn (Y. Xie), lvkun.1987@stu.xjtu.edu.cn (K. Lu), zhang_di@mail.xjtu.edu.cn (D. Zhang).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.10.029

the physical process of energy extraction from a uniform flow through a flapping foil using a fluid-structure interaction model based upon Navier–Stokes solver. In their approach a prescribed pitching motion of the foil was used to induce unsteady time-dependent forces and moments for foil plunging motion, which was utilized for energy extraction. However, a positive net energy extraction was achieved only at low oscillating frequency. A further study on the optimal frequency for flow energy harvesting of a flapping foil was conducted by Zhu [10]. The results show that flow energy extraction is closely related to efficient evolution of the wake and the maximum energy harvesting efficiency occurs under the constraint that there is significant vortex shedding from the leading edge at sufficiently large effective angles of attack. Inspired by the ability of fish extracting energy from unsteady flows and vortical structures, Simpson et al. [11] experimentally studied the energy extraction performance of flapping foils at $Re = 13{,}800$ with various motion parameters considered. Overall efficiencies of up to $43 \pm 3\%$ are achieved with simple sinusoidal motions. The concept of hydrokinetic turbine using oscillating hydrofoils to extract energy from water currents (tidal or gravitational) was presented and tested in the investigation of Kinsey et al. [12]. The results show the best power extraction efficiency of 40% once the overall losses in the mechanical system were taken into account. The 40% hydrodynamic efficiency exceeds expectation and reaches levels comparable to the best performances achievable with modern rotor blades turbines.

More recently, some researchers pay attention to the effects of nonsinusoidal motion on energy extraction performance of an oscillating foil. In the numerical study of an oscillating foil by Young et al. [13] and Ashraf et al. [14], an alternative nonsinusoidal foil motion was applied for wind and hydropower generator. With the nonsinusoidal motions used, the plunging motion was maintained for as long as possible at a relatively high velocity and followed by rapid pitching reversals. The results for a NACA0014 foil undergoing nonsinusoidal pitch-plunge motion leads to around 17% increase in output power and 15% increase in efficiency over that for sinusoidal motion. In the research by Xiao et al. [15], a proposed trapezoidal-like pitching motion combined with a sinusoidal plunging motion was used to realize a non-sinusoidal trajectory. They reported that nonsinusoidal motion increases the power output and efficiency by around 50% over their tested range of parameters.

Of all the foils in the above studies, without exception, oscillate with traditional flapping motion. In this paper a modified flapping motion is proposed. The purpose of this paper is to systematically evaluate and quantify the energy extraction performance of a foil with modified flapping motion.

2. Numerical method

2.1. Solver

In order to simulate the unsteady flow field around the 2-D foil section, the commercially available CFD package ANSYS CFX 13.0 with an unsteady incompressible and viscous flow solver is applied. A bounded second order upwind based discretization is used for convection and diffusion terms, and a second-order-accurate backward implicit scheme is used for time discretization. Additionally, the mass flow is evaluated such that a pressure–velocity coupling is achieved.

In the present study the foil is modeled as an ellipse of 10% thickness. In order to compute the flow around moving foil we use two zones of grids with a sliding grid interface. The foil is located in the center of the inner zone and an O topology mesh is generated to model the foil. The boundaries of the mesh are located at 35 chords upstream of the leading edge, 50 chords downstream of the trailing edge and at 35 chords from the upper and lower surface of the foil, such that the influence of the far-field boundary condition is negligible. A no-slip boundary condition is applied along the foil surface and the boundary-layer mesh used a first cell distance of 10^{-5} chord with a y^+ value less than 1. To simulate the modified flapping motion, a moving mesh technique is employed, as used by Ashraf et al. [14]. A CFX expression language (CEL) subroutine developed and attached to the CFX solver is used to control the dynamic mesh motion. In this paper, all the cases are studied at $Re = 10^4$ and the flow field is assumed to be laminar, as the simulations in Xiao et al. [15] and Young and Lai [16]. Besides, for all the simulations 6 flapping cycles are calculated and it takes 2 cycles for the results to reach steady state.

2.2. Kinematics

We define the modified flapping motion experiencing simultaneous pitching motion $\theta(t)$ and plunging motion $h(t)$. Fig. 1(a) shows the downstroke and upstroke of the modified flapping motion, and the traditional flapping foil is shown in Fig. 1(b). The plunging motion of the modified flapping motion is governed by equation expressed as follow:

$$h(t) = H_0 c \sin(2\pi f t) \tag{1}$$

where H_0 is the nondimensional plunging amplitude, c is the foil chord length and f is the flapping frequency. The pitching motion of the modified flapping motion (Fig. 1(a)) is governed by equation expressed as follow:

$$\theta(t) = \frac{\pi}{2} + \theta_0 \sin(2\pi f t + \varphi) \tag{2}$$

where θ_0 is the pitching amplitude and φ is the phase difference between pitching and plunging motions. For the elliptical foil the pitch axis is located at midchord. To obtain the maximum vertical area swept by the foil for power output, φ is kept constant at 90°, as employed by Kinsey and Dumas [5] and Xiao et al. [15]. Thus value of $\theta(t)$ varies from $\pi/2 - \theta_0$ to $\pi/2 + \theta_0$ in a cycle. The effective angle of attack α_e for the foil with modified flapping motion can be expressed as:

$$\begin{cases} \alpha_e = \pi - \theta(t) - \arctan\left(\frac{V_Y}{U_\infty}\right), & V_Y \geq 0 \\ \alpha_e = -\theta(t) - \arctan\left(\frac{V_Y}{U_\infty}\right), & V_Y < 0 \end{cases} \tag{3}$$

where V_Y is the plunging velocity and U_∞ is the free stream velocity. As for traditional flapping foil [3–15] (Fig. 1(b)), the leading edge and trailing edge are unalterable. The maximum and minimum absolute values of angles of attack (AOA) occur around the mean and maximum plunging position, respectively. Besides, the maximum α_e occurs around the mean plunging position. The pitching motion is mainly used to realize the change in the direction of lift force and the lift force together with plunging motion is mainly applied for energy extraction. Thus the power can be generated in both the downstroke and the upstroke due to the synchronization between the vertical force and the plunging velocity. Similar energy extraction process can also be realized by the proposed modified flapping motion. While for modified flapping motion, the leading and trailing edges of the foil are alterable (Fig. 1(a)). Thus using an elliptical airfoil and pitching at half chord help to make sure that the airfoil has the same leading edge shape and the distance between the pitching axis and the leading edge