Ocean Engineering xxx (2017) 1–11

Contents lists available at ScienceDirect

Ocean Engineering

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

A case study on tandem configured oscillating foils in shallow water

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ARTICLE INFO

Keywords:
Oscillating-foil turbine
Shallow water
Tandem configuration
Renewable energy

ABSTRACT

Previous research on the oscillating-foil turbine system has demonstrated its great potential for energy extraction. However, not much is known about the interaction of this device with its working environment. To determine the performance and environmental impact of an oscillating-foil turbine in shallow water, a case study have been conducted which was made of the dual oscillating energy extraction foils system with a tandem configuration which operates at two different water depths: i.e., $D = 5c$ and $D = 10c$. The performance and the environmental effects of the device were compared between shallow-water and deep-water cases. The results show a 10% efficiency loss in the $D = 5c$ case compared with that of the deep water case, because of the interaction between the oscillating-foils and the seabed. It is also observed that the foil vortices dissipation rate of the $D = 5c$ case is 13% less than that of the deep-water case due to the free-surface effect. The water level also rises 23% around the oscillating-foils location of the $D = 5c$ case because of the blockage effect of the device.

1. Introduction

The renewable-energy industry plays an important role in the energy field today. Research into renewable-energy devices accordingly provides key support for the renewable-energy industry, as it helps the industry overcome challenges and foresee opportunities. There are three general types of tidal/wind renewable-energy devices: horizontal axis turbine (HAT), vertical axis turbine (VAT) and oscillating-foil turbine (OFT). Compared with conventional turbines (i.e., HAT and VAT), the OFT is a novel device which requires more research to boost its commercialization process.

McKinney and DeLaurier first extracted wind energy in 1981 using the harmonically oscillating foil (McKinney and DeLaurier, 1981). They designed a horizontally-aligned foil with a symmetrical aerofoil cross-section. McKinney and DeLaurier (1981) found that, with a prescribed combination of pitching and heaving motions, the output power and efficiency could be accomplished for both theoretical analyses of unsteady-foil aerodynamics and for wind-tunnel experimental tests.

Followed by McKinney and DeLaurier's work, many researchers studied the mechanism and energy extraction efficiency of the oscillating foil (Jones et al., 1997; Jones et al., 1999; Davids, 1999; Lindsey, 2002; Jones et al., 2003; Zhu, 2011; Xiao et al., 2012; Campobasso et al., 2012; Liu et al., 2013; Le et al., 2013). Among the many researchers, Kinsey and Dumas (2008, 2011; 2012a, 2012b; 2014) carried out a series of studies on the oscillating-foil via experimental and numerical simulations recently.

Kinsey and Dumas (2008) carried out a detailed analysis of the mechanism of the energy-extraction type of oscillating foil. They report a maximum energy-extraction efficiency of 34% with reduced frequency between 0 and 0.25, a pitching amplitude between 0° and 90°, a heave amplitude of one chord length, a Reynolds number of 1 100 and an NACA0015 foil shape. They also report that the energy-extraction efficiency is greater than 20% when the pitch amplitude is greater than 55°. Their results indicate that the heave amplitude and the oscillating frequency play a more significant role in energy-extraction performance than foil geometry plays.

Kinsey and Dumas (2012a) carried out a three-dimensional numerical calculation of the foil-oscillating turbine. They report that the hydrodynamic losses of the three-dimensional effect can be limited within 10% when endplates that use a foil tip with an aspect ratio larger than 10 are compared with the two-dimensional results. A non-horizontal hydrodynamic flow of up to 30° with respect to the foil chord was also considered. They report that the energy-extraction performance is proportional to the projected energy flux.

Kinsey and Dumas (2012b) investigated two-dimensional, dual-oscillating foils with tandem configurations. Both of the foils could share the same flow stream under this arrangement to allow the oscillating foils to achieve their highest efficiency. Kinsey and Dumas report a beneficial effect from the interaction between the downstream vortex and the downstream foil which led to a total system efficiency of 64% under the optimized working condition. However, a harmful effect was also observed from the vortex-foil interaction, which leads the downstream

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https://doi.org/10.1016/j.oceaneng.2017.09.059
Received 26 June 2017; Received in revised form 16 August 2017; Accepted 25 September 2017
Available online xxxx
0029-8018/

Nomenclature

A	sweep area of the oscillating foils (m^2)
c	blade chord length (m)
$c_d(t)$	instantaneous drag coefficient
$c_l(t)$	instantaneous lift coefficient
$c_m(t)$	instantaneous moment coefficient
c_{op}	foil power coefficient
c_{pit}	pitch centre of each foil from its leading edge (m)
D	water depth measured from the free surface to the seabed in calm water (m)
f^*	reduced frequency of oscillating foil
f_0	foil oscillating frequency (Hz)
$h(t)$	instantaneous heave of foil (m)
h_0	foil heave amplitude (m)
M	foil moment relative to the foil pitch centre (Nm)
p_o	instantaneous power of the system (W)
S	gap between the upstream and the downstream foil (m)
t	instant time (s)
T	oscillating period of the system (s)
U_∞	incoming flow velocity (m/s)
$V_t(t)$	foil instantaneous resultant velocity (m/s)
X	axis in horizontal (m)
$x_l o_l y_l$	body-fitted coordinate
Y	axis in vertical (m)
$\alpha(t)$	foil instantaneous angle of attack (deg)
η	system energy-extraction efficiency
$\theta(t)$	instantaneous pitch of foil (deg)
θ_0	foil pitch amplitude (deg)
ρ	fluid density (kg/m^3)
φ	phase difference between heave and pitch of foil
ψ	phase difference between upstream and downstream of foils

foil to make a negative contribution to the system's energy-extraction efficiency. In comparison with the experimental results, the numerical simulations were over-predicted with respect to the peak-power coefficient. This may be because of the broken, two-dimensional coherence of the vortices in the three-dimensional experiments.

Kinsey and Dumas (2014) tested a single oscillating-foil turbine by using a two-dimensional, unsteady RANS solver. They report a maximum efficiency of 43% under a Reynolds number of 500,000. According to their results, better energy-extraction efficiency can be achieved when the effective angle of attack is around 33°. They also report that the leading-edge vortices are not necessary around the best-performance region with high Reynolds number rather than the phenomenon at a low Reynolds number.

Most recently, Liu et al. (2016) designed a passive trailing-edge flexible oscillating foil for energy extraction by using a metal stiffener to control the stiffness of the trailing edge and a PDMS rubber to form the foil shape. They tested two types of material for the stiffener, which proves the beneficial effect of their passive trailing-edge flexible design on the energy-extraction efficiency of the oscillating-foil turbine. They also separately simulated and studied the Young's Modulus effect and the density-ratio effect of the stiffener by using virtual materials. Empirical equations that relate Young's modulus to energy-extraction efficiency were developed based on their study. The mechanism of this phenomenon was also investigated based on vortices analysis.

Most previous studies focus on the oscillating foil itself in terms of foil/motion optimization or the interaction of multiple foils. However, there has been little study of the interaction between the oscillating foil system and its working environment. The present case study investigates a tandemly arranged, dual oscillating-foils energy-extraction system which operates in shallow water. Two different water depths—i.e., five and 10 times foil chord length—are studied and compared with deep-water cases. The system performance, vortices structure and free-surface level are investigated under present working conditions.

Section 2 lists the problem description, mathematical formulations and numerical algorithms and validations/verifications of the present study. Section 3 presents results concerning energy-extraction performance in different water depth, vortices structure in near-foil and wake regions, free-surface level and flow trajectory. Finally, the conclusions of the study and suggestions for future work are summarised in Section 4.

2. Problem formulation and numerical methodology

2.1. Problem description

The present case study considers a two-dimensional, tandemly arranged, oscillating-foils energy-harvesting system working in shallow water. A schematic plot on the oscillating-foils energy-harvesting system is shown in Fig. 1. Please refer to Xiao and Zhu (2014) for the three-dimensional design of the oscillating-foils turbine. Since the present study is focusing on two-dimensional simulations of the oscillating-foils turbine, only 2D schematic diagram is presented herein. Two NACA0015 hydrofoils with a gap of S and a chord length of c were immersed and oscillated (combined with heave and pitch motion) in a uniform, viscous water flow with a velocity of U_∞. The Reynolds number based on the foil chord length is 5×10^5. These foils pitch at $c_{pit} = 1/3$ chord length, as measured from their leading edge. The oscillating-foils system is assumed to be bottom-seated. The distance between the foil and the seabed is keep changing during the operation of the system. In the present study, the closest distance from the pitch axis of the foil to the seabed is equal to one chord length, c, and the longest distance from the pitch axis of the foil to the seabed is one chord length plus two heave amplitude for all shallow water cases. Two water depths, D, which measure the distance from the free surface to the seabed in calm water were investigated: i.e., $D = 5c$ and $D = 10c$. Since the system is bottom-seated, different depths result in different distances from the system to the free surface, while the distance from the system to the seabed remains the same for all shallow water cases as mentioned above. A simulation of the oscillating-foils system under deep-water conditions—which assumes that the system is infinitely far from both the free surface and the seabed—was also carried out for comparative analysis. The incoming flow was simulated as calm water, which means no wave was generated from the inlet boundary.

2.1.1. Kinematics for oscillating foils

In the present study, the motion of the oscillating foils is simplified

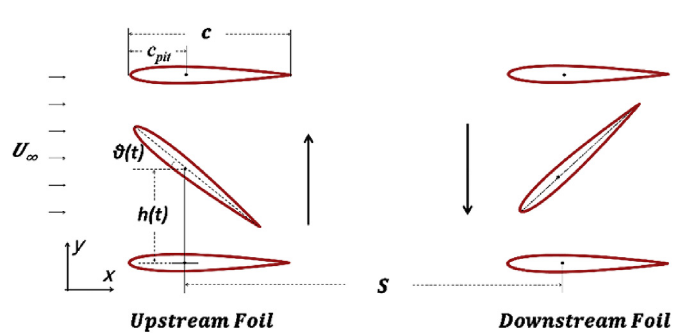

Fig. 1. Schematic diagram for oscillating energy extraction foils with tandem configuration.