Journal of Fluids and Structures 69 (2017) 1–15

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Numerical investigation into energy extraction from self-induced oscillations of an elliptical plate

W. Jiang[a], D. Zhang[b], Y.H. Xie[a,*]

[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

Keywords:
Oscillating foil
Energy extraction
Vortex-induced vibration
Renewable energy

ABSTRACT

A new concept of power generator using self-induced oscillating foil to extract energy from fluid is proposed and tested in the present study. The pitching motion of the elliptical foil is induced by the downward shed vortexes of the foil. Two-dimensional Navier-Stokes simulations at $Re=10^4$ are conducted to study the fluid-foil interaction as well as the performance of energy extraction. Three kinds of motion trajectories are concerned, i.e. pitching motion, pitching motion combined with streamwise plunging and pitching motion combined with transverse plunging. The investigations are undertaken over a wide range of structural parameters (mass ratio, stiffness factor and damping coefficient). Numerical results reveal that the pitching motion combined with transverse plunging can achieve best energy extraction performance. With well-tuned structural parameters, the power generator can reach maximum power coefficient of 32% and energy extraction efficiency of 20%. Hence, it demonstrates that the promising self-induced oscillating foil can achieve satisfactory energy extraction performance without pitching motion actuator.

1. Introduction

With continuous rise of energy demand and fuel price in the world, new renewable energy technologies have drawn gradually more attentions and resources from the academic world and governments. No such single renewable energy resource can meet the world's growing energy needs. In the past decade, humankind has tapped into a variety of renewable resources, and recognizes hydrokinetic and wind energy as significant and still promising contributors to the renewable energy share. Several reviews have summarized the most-advanced hydrokinetic energy conversion technologies (Lago et al., 2010; Laws and Epps, 2016). Two kinds of conversion technologies of flow energy, namely vortex-induced-vibration systems and oscillating hydrofoils or airfoils systems, will be introduced in this paper. Based on these two concepts, a new power generator using self-induced oscillating elliptical plate to extract energy from fluid is proposed and numerically tested.

The bluff body in fluid flow commonly undergoes large oscillations due to boundary layer separation and formation of vortices. The phenomenon of vortex-induced vibration of cylinders has been well studied. It has a transverse responding to the fluid flow. In order to take advantage of this phenomenon, the slender bluff body is mounted over springs with specific stiffness so that large sustained oscillations can be achieved. The VIVACE (vortex induced vibration aquatic clean energy) converter developed by Bernitsas and Raghawan (Bernitsas et al., 2008) has followed this idea. Their design based on the idea of maximizing rather than

---

[*] Corresponding author.
E-mail addresses: jiangwei@mail.xjtu.edu.cn (W. Jiang), zhang_di@mail.xjtu.edu.cn (D. Zhang), yhxie@mail.xjtu.edu.cn (Y.H. Xie).

http://dx.doi.org/10.1016/j.jfluidstructs.2016.11.006
Received 30 March 2016; Received in revised form 27 October 2016; Accepted 9 November 2016

Nomenclature

A	plunging amplitude
c	foil chord length
c_x	streamwise damping coefficient
c_y	transverse damping coefficient
c_θ	rotational damping coefficient
C_L	lift coefficient
C_D	drag coefficient
C_M	torque coefficient
C_p	pressure coefficient
C_P	power coefficient
$C_{P\mathrm{mean}}$	time-averaged power coefficient
d	vertical extent of the foil motion
f	plunging oscillation frequency
f_{Nx}	streamwise natural frequency
f_{Nx}	transverse natural frequency
$f_{N\theta}$	rotational natural frequency
f_S	vortex shedding frequency
$F_x(t)$	streamwise fluid force (drag force)
$F_y(t)$	transverse fluid force (lift force)
$h(t)$	plunging motion
I	moment of inertia
I_d	displaced moment of inertia
I^*	moment of inertia ratio
k_x	streamwise stiffness factor
k_y	transverse stiffness factor
k_θ	rotational stiffness factor
m	foil mass
m_d	displaced fluid mass
m^*	mass ratio
$M(t)$	torque
r	relative foil thickness
Re	Reynolds number
t	physical time
T	flapping motion period
U_x^*	reduced velocity based on f_{Nx}
U_y^*	reduced velocity based on f_{Ny}
U_θ^*	reduced velocity based on $f_{N\theta}$
U_∞	free stream velocity
$V_x(t)$	streamwise plunging velocity
$V_y(t)$	transverse plunging velocity
W_T	energy output per cycle
η	energy extraction efficiency
θ_0	pitching amplitude
$\theta(t)$	pitching motion
ρ	fluid density
ζ_x	streamwise damping factor
ζ_y	transverse damping factor
ζ_θ	pitching damping factor
$\omega(t)$	angular velocity

spoiling vortex shedding and exploiting rather than suppressing VIV. They found that experimental models could maintain VIV over a broad range of vortex shedding synchronization and corresponding broad ranges of Reynolds number. The above VIVACE model was then tested in a Low Turbulence Free-Surface Water Channel (Bernitsas et al., 2009). The influence of some key parameters, i.e. the mass ratio, the mechanical damping, the Reynolds number, and the aspect ratio were studied. The peak efficiency achieved for the tested VIVACE model was 0.308, and the corresponding integrated power efficiency was 0.22. Barrero-Gil (Barrero-Gil et al., 2010) built a theoretical model and established the relation among mass, mechanical properties, cross-section geometry, flow velocity and energy efficiency. It demonstrated that nonlinear springs might be useful to improve the power generating performance of an oscillating body by expanding the amplitude response. More recently, Narendran (Narendran et al., 2016) experimentally investigated the efficiency of a vortex induced vibration hydrokinetic energy device, and reported peak mechanical efficiency value around 90% with corresponding time average value about 50%, using linear generator at Re of the order (10^5). As pointed out by Bernitsas (Bernitsas et al., 2008), the VIVACE converter or VIVEC (Vortex Induced Vibration Energy Converter) has many advantages. To name just a few, it is friendly to the marine life and coastal real estate; it is simple with all mechanical and electrical components; robustness and at least a 20 yr life; broad range of synchronization. Nevertheless, its low power coefficient and efficiency may lead to a high cost and thus limiting its applications. According to above studies, we can find that the VIVACE convector commonly moves in the transverse direction and thus having only one degree-of-freedom, so the AOA of the bluff body remains unchanged during the energy extraction process, which limits the lift force and the ability of harvesting energy.

Another available design is to use an oscillating or flapping wing to extract energy from the flow. This concept was first demonstrated and tested as a wind energy harvester by McKinney and DeLaurier (McKinney and DeLaurier, 1981) in 1981. Following this novel concept, the energy extraction performance of the flapping foil with fully prescribed motion (Young et al., 2014) has been systematically studied by many researchers (Jones and Platzer, 1997; Davids, 1999; Dumas and Kinsey, 2006; Kinsey and Dumas, 2008, 2014; Xiao et al., 2012). According to these studies, the optimal reduced frequency corresponding to the peak efficiency was observed within the range from 0.10 to 0.15. The energy harvesting efficiency increased significantly with the plunging amplitude at low plunging amplitudes, while the efficiency decreased once the plunging amplitude reached one chord length. Besides, it was found that the peak energy extraction occurred when the pitching and plunging motions was 90° out of phase and the maximum effective angle of attack was near 33°. Following the flapping kinematics studies of the fully prescribed motion, some new prototypes and designs with semi-passive or fully passive motion were proposed (Xiao and Zhu, 2014). These flapping foil generator concepts are categorized by their activation mode (Young et al., 2014). In the semi-passive mode, a motor was used to drive the pitching motion, while the plunging motion was driven by the fluid and the power was extracted from the plunging motion (Zhu and Peng, 2009; Huxham et al., 2012). In the fully passive mode, all motions were driven directly by the fluid. The foil was restrained to move with one single degree of freedom, where the pitching motion was linked to the plunging motion via the Geneva Wheel (Young et al., 2010; Young et al., 2013) or the crankshaft (Kinsey et al., 2011), or was allowed to move in pitch and plunge independently (Peng and Zhu, 2009; Zhu, 2012; Veilleux, 2014). The semi-passive systems have been adopted in industrial prototypes. The first industrial prototype of an oscillating foil turbine was the 150 kW tidal stream generator from the Engineering Business Ltd (Limited