Journal of Fluids and Structures 72 (2017) 96–113

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Structural response and energy extraction of a fully passive flapping foil

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ARTICLE INFO

Article history:
Received 26 January 2017
Received in revised form 25 April 2017
Accepted 5 May 2017

Keywords:
Flapping foil
Energy extraction
Flow-induced vibration

ABSTRACT

The structural response and energy extraction of a foil undergoing two-degree-of-freedom fully passive flapping motions in a two-dimensional flow are numerically investigated at $Re = 400$. The simulations of the fluid–structure interaction were conducted using the Immersed Boundary Method (IB Method). In the parametric space of flow reduced velocity and pivot location investigated, five response regimes are identified. This paper focuses on the stable synchronisation regime, which is characterised by harmonic wake-body synchronisation with stable large-amplitude oscillations. Correspondingly, a novel wake pattern composed of a triplet of vortices and a pair of vortices shed per cycle, referred to as T+P pattern, is encountered. An analysis of the dynamic nonlinearity showed that the inertia forces can induce perturbations in the form of harmonics to the dynamics of the system. Furthermore, the highest cycle-averaged power output coefficient and efficiency were found to be $\bar{C}_P = 0.95$ and $\eta = 0.32$, respectively. The present results suggest that high-efficiency case in fully passive flapping motions is associated with a large pitch–plunge phase and a 2S wake pattern composed of two strong single LEVs shed per cycle.

1. Introduction

Flow energy harvester based on flapping foils, as a novel design motivated by rapidly increasing demand for renewable energy, has been received a great deal of research attention in the last two decades. In contrast to conventional rotary turbines that require the flow remaining attached to the blades for high aerodynamic performance and efficiency, flapping foils utilise an aerodynamic mechanism involving leading-edge vortices (LEVs) to augment aerodynamic/hydrodynamic lift and performance. Such an aerodynamic mechanism has been widely seen in insect/bird flights and aquatic locomotion in nature (see Ellington et al., 1996; Srygley and Thomas, 2002; Birch et al., 2004). Inspired by bio-applications, flapping foils are practically considered as an alternative to rotary turbines for energy harvesting (see McKinney and DeLaurier, 1981). This has motivated extensive investigations that aim to characterise the fluid–structure mechanism and assess the energy harvesting performance of flapping foils. Comprehensive reviews of this subject have recently been given by Xiao and Zhu (2014) and Young et al. (2014).

Assuming that two degrees of freedom of plunge (or heave) and pitch are allowed, flapping foil flow energy harvesters are generally classified by their activation mode into three categories (Xiao and Zhu, 2014; Young et al., 2014): (i) fully forced system with motions that are fully prescribed in both plunge and pitch, (ii) semi-passive system with motions that usually

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.05.002
0889-9746/

have prescribed pitching motion but free plunging motion, and (iii) fully passive system with free plunging and pitching motions, fully determined by the fluid–structure interaction.

With its simplicity in modelling, a foil undergoing fully forced motions, which mostly are prescribed as sinusoidal, has been extensively studied. Previous studies have shown that energy-extraction performance is strongly related to pivot location, oscillation frequency and plunging amplitude, and the relative phase of pitching and plunging motions (see Kinsey and Dumas, 2008; Platzer et al., 2010; Ashraf et al., 2011; Zhu, 2012; Xiao and Zhu, 2014). In a systematic study, Davids et al. (1999) predicted a max efficiency of 0.30 and also found that the optimum phase reduced as the pivot was moved towards the trailing edge. Kinsey and Dumas (2008) presented a mapping of energy-extraction efficiency in the parametric space of reduced frequency and pitching amplitude for a NACA0015 foil that had a fixed plunging amplitude, a fixed phase of 90° and a given pivot location, in which the highest efficiency was found to be 0.34. Further, Zhu (2011) observed that the efficiency was maximised when the imposed flapping frequency matched the most unstable frequency of the wake that was associated with multiple LEVs, suggesting the feasibility of high-efficient energy extraction of a fully passive system.

Considerable attention has also been given to semi-passive systems that allow the foil to plunge freely while it undergoes prescribed pitching oscillations (e.g. Zhu and Peng, 2009; Abiru and Yoshitake, 2011; Wu et al., 2015). Recently, Deng et al. (2015) investigated the effects of reduced frequency, mass ratio and rotational inertia on the efficiency of a semi-passive system. They observed a maximum efficiency of 0.34 with an optimum set parameters of reduced frequency and pitching amplitude, and also found that the efficiency decreased monotonically as the mass ratio was increased.

Compared to fully forced or semi-passive systems, there has been much less work that investigates a fully passive system. This is partly because it is challenging to experimentally or numerically model such a system that involves with complicated problems of coupled fluid–structure interaction and nonlinear coupling in two-degree-of-freedom (2-DOF) flapping motions. Similar to fully forced and semi-passive systems, Peng and Zhu (2009) found that the interaction between the LEV and the foil can enhance energy harvesting performance in fully passive motions. Moreover, they suggested that the pivot location is an important factor to the energy harvesting capacity. Simulations of fully passive motions by Platzer et al. (2010) reported a maximum efficiency 0.30, which was well predicted by prescribed motions. Young et al. (2013) identified a broad region of high efficiency with a maximum value of 0.294. It should be noted that, in the studies of Platzer et al. (2010) and Young et al. (2013), their analysis is simplified by reducing the system from two DOFs (plunge and pitch) to one DOF (flywheel angle). The phase by which pitching motion leads plunge motion was fixed at 90°. Zhu (2012) suggested that full passive systems may be much more adaptable to various real applications than fully forced or semi-passive systems. More recently, Veilleux and Dumas (2017) achieved a peak efficiency 0.34 in an optimised fully-passive system at a high Reynolds number of 500 000, which was enhanced by the adequate synchronisation between both plunging and pitching motions. These results indicate that fully passive systems can achieve comparable energy extraction performance to fully forced or semi-passive systems.

While most previous studies of flapping foils assumed that the foil mass was negligible, investigations of flow-induced vibrations (FIVs) of bluff bodies have shown that the mass ratio, defined as the ratio of the total mass of the oscillating system to that of the displaced fluid, is an important parameter in the fluid-structural mechanism. FIVs of bluff bodies at low mass ratio can exhibit a rich variety of dynamic characteristics and wake structures as a function of reduced velocity, which is significantly different to high-mass-ratio case (see Govardhan and Williamson, 2000; Zhao et al., 2014a,b).

A clear gap in the literature is the lack of detailed knowledge of the fluid–structure interaction mechanism of a fully passive flapping foil, including characteristics of vibration response, dynamic nonlinearity, and wake patterns. Therefore, this paper specifically examines the following aspects: (i) regimes of the vibration response and corresponding flow patterns in a parametric space of pivot location and reduced velocity, (ii) effects of the inertia forces on the dynamic nonlinearity, and (iii) the performance of energy extraction.

The rest of this paper is structured as follows. The fluid–structure system modelling and the numerical method are described in Section 2. The results and discussion, including the structural response, an analysis of the dynamic nonlinearity, and the energy extraction performance are presented in Section 3. Finally, conclusions are drawn in Section 4.

2. Numerical approach

The fluid–structure system modelling is described in Section 2.1. Details concerning the dynamics of the foil are given in Section 2.2. A brief description of the mechanism of power generation of the hydro-elastic system is presented in Section 2.3. The numerical method employed for the flow dynamics is presented in Section 2.4 and its validation is given in Section 2.5.

2.1. Fluid–structure system

The current paper investigates the dynamic response and the energy transfer of an elastically mounted NACA0012 foil in a free-stream, as shown in Fig. 1. The fluid density and dynamic viscosity, and the free-stream velocity are denoted by ρ, μ and U, respectively. The foil is constrained to plunge (or heave) in the cross-flow direction and free to pitch about a pivot point. The instantaneous plunge displacement is denoted by $h(t)$, which can be non-dimensionalised by the foil chord (c) as $h^*(t) = h/c$. The pitch displacement is denoted by $\theta(t)$, and it is normally measured in radian in this study. The instantaneous transverse fluid force and pitching moment are denoted by $F_h(t)$ and $M_\theta(t)$, respectively. The structural damping coefficient in plunge is designated by c_h. The structural stiffness constants are designated by k_h and k_θ in plunge