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Effects of non-sinusoidal pitching motion on energy extraction performance of a semi-active flapping foil

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A B S T R A C T

Numerical simulations are used to study the energy harvester based on a semi-active flapping foil, in which the profile of the pitching motion is prescribed and the heaving motion is activated by the vertical hydrodynamic force. We consider a two-dimensional NACA0015 airfoil with the Reynolds number $Re = 1000$. First, for the sinusoidal pitching, an optimal combination of the parameters of pitching amplitude $\theta_0 = 75^\circ$ and reduced frequency $f^* = 0.16$ is identified, with the highest energy harvesting efficiency of 32% being recorded. Then we study non-sinusoidal pitching, with a gradual change from a sinusoid to a square wave as β is increased from one. We find that its effect of efficiency enhancement is limited for the parameters approaching their optimal values, and the upper boundary of the efficiency appears not to be increased. In detail, we report that when the pitching amplitude is small, non-sinusoidal pitching motions can indeed improve the performance of the system. However, when both the pitching amplitude and the flapping frequency are close to their optimal values, non-sinusoidal pitching motions contribute negatively to the harvesting efficiency. We suggest that a non-sinusoidal profile, at least a simple trapezoidal-like one is ineffective in the semi-active system reported by the current study.

1. Introduction

Rivers and ocean are promising sources supplying people renewable and clean energy for their abundance of flow energy. Harvesting flow energy through flapping foil is a novel method inspired by aquatic animals, whose swimming is believed to have many advantages such as high speed, high efficiency and low noise [1]. Compared to traditional rotary turbines, the flapping foil system benefits from the simple idea of using translational motions instead of rotation, thus bringing about many advantages, e.g. it does not include fast rotating blades which are threats to aquatic animals, and it is easier to manufacture compared to the complicatedly shaped blades used in traditional turbines. Moreover, it is feasible to be planted in shallow water and in groups because their sweeping windows are rectangular [2].

It was originally declared that a flapping foil was capable of extracting energy from an unsteady current, such as a surface wave [3,4]. Decades ago, McKinney and DeLaurier [5] proposed the concept of extracting flow energy through the flapping motion of an airfoil. Their original prototype was a windmill utilizing harmonically oscillating wing to extract wind energy. Usually, a flapping foil used for energy harvesting undergoes a coupled pitching and heaving motions. According to its degrees of freedom, this system can be categorized into three types, which are fully-active system, semi-active system and purely passive system respectively [6,7]. The performance of an energy harvester depends on its mechanical and kinematic parameters. The mechanical parameters include the pivoting location of the foil, the shape of the foil and the damping (for semi-active or fully passive systems). The kinematic parameters include the flapping frequency, the pitching amplitude, the heaving amplitude and the phase difference between the pitching and heaving motions. Extensive work has been carried out on fully-active systems [8–10]. Kinsey and Dumas [11] studied the power-extraction efficiency of a single oscillating airfoil with the reduced frequency in the range of 0–0.25 and pitching amplitude from 0° to 90°. In their studies, the efficiency reached as high as 35%. This high efficiency was also confirmed by experiments [12], in which two oscillating hydrofoils in tandem arrangement were tested. The rotating shaft driven by oscillating

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hydrofoils was precisely controlled by an electrical drive, therefore a constant angular velocity was guaranteed. Moreover, it was reported that the energy harvesting efficiency of the flapping foil is related to the stability of the wake behind it [13]. The 'foil-wake resonance' coincides with the maximum energy harvesting efficiency. Performance of a flapping foil flow energy harvester in shear flows was investigated by Cho and Zhu [14]. It should be pointed out that the aspect ratios of foils are finite in realistic working conditions, though most previous research was based on 2-D assumptions. Shao et al. [15] investigated the wake structures of wings with different aspect ratios. Deng et al. [16] suggested that an aspect ratio around $AR = 4$ was the most appropriate choice for a real energy harvesting system with a sinusoidal pitching motion.

Though most of the above mentioned studies concentrated on fully-active flapping foil systems, semi-active system and fully passive system are more practical for energy harvesting. The performance of a semi-active flapping foil energy harvester has been investigated by Zhu and Peng [17]. They suggested that the performance depended on mechanical parameters including the magnitude of the damping and the location of the pitching axis, as well as operational parameters, e.g. the pitching frequency and pitching amplitude. A fully passive flapping foil system was examined by Peng and Zhu [18], who modeled the system by mounting a flapping foil on a damper and a rotational spring. Four different responses were recorded, and stable energy could be obtained when periodic pitching and heaving motions were both periodically excited. The response of a purely passive flapping foil flow energy harvester in a linear shear flow was also investigated [19]. It was indicated that in shear flows the devices were still capable of undergoing periodic responses as in uniform flows, which was essential for reliable energy harvesting. Young et al. [20] studied a fully passive flapping foil, declaring an efficiency as high as 41%. Huxham [21] conducted experiments on an oscillating foil energy converter undergoing a prescribed pitching motion with the heaving motion determined by unsteady hydrodynamic forcing on the foil.

In recent years, strategies to enhance energy extraction capacity have been reported. Wu et al. [22,23] found that the power extraction performance could be improved by placing the foil near a wall. Inspired by the observations that some animals such as turtles and birds flap their fins or wings in an asymmetrical fashion, people studied in-line motions of flapping foils which could cause high thrust and high efficiency [24,25]. Non-sinusoidal oscillating motions have also been introduced to enhance the efficiency of energy harvesting system. Xiao et al. [26] adopted a trapezoidal-like pitching profile, by varying the key parameter which controls the shape of the pitching profile they found an optimal profile which was proved to dramatically increase the power output and energy harvesting efficiency over a wide range of Strouhal numbers. Ashraf et al. [27] reported that 15% enhancement of efficiency could be achieved by adopting non-sinusoidal pitch-plunge motions. A comparison between the effects of different non-sinusoidal motions was carried out by Lu et al. [28]. They found that an appropriate combination of non-sinusoidal pitching and non-sinusoidal plunging motions had the potential to provide the best energy harvesting performance. According to the numerical simulations by Xie et al. [29], they believed that relatively high flapping frequency and large pitching amplitude should be chosen for the best energy harvesting performance. Though all studies reviewed above focused on fully-active flapping foils, their efforts indicate a possibility of increasing the efficiency of a semi-active harvester by adopting non-sinusoidal pitching motions. However, we note that none of these studies has covered the optimal parametric range in which the highest efficiency for sinusoidal motion has already been achieved. We list their chosen parameters as the following. In the study by Xiao et al. [26], two nominal angles of attack, $\alpha_0 = 10°$ and $\alpha_0 = 20°$, were adopted. Lu et al. [28] selected a nominal angle of attack $\alpha_0 = 15°$. Xie et al. [29] covered the range of pitching amplitude θ_0 from 0° to 35°. According to the report by Kinsey [11], these parameters are out of the best-performance parametric range. As pointed out by Deng et al. [16] that the increasing effect of non-sinusoidal pitching amplitude on efficiency was weak as θ_0 approaching its optimal value. Platzer et al. [30] also indicated that the feasibility of efficiency enhancement by non-sinusoidal motions at different operation parameters had not been well investigated. Therefore, clarification on this issue is needed by adopting a wider parameter range.

In this paper, we use numerical code based on finite-volume method to solve the two-dimensional Navier–Stokes equations. The flow by a semi-active flapping foil is simulated with prescribed pitching profiles while the heaving motion is determined by the hydrodynamic force acting on the foil. We consider a two-dimensional NACA0015 foil, with the Reynolds number of 1000 calculated by the incoming flow velocity, the chord length and the properties of the fluid. As a basis for further investigations, firstly, we carry out a parametric study on a flapping foil with sinusoidal pitching motion. In order to study the appropriateness of non-sinusoidal pitching motions on improving the energy extraction performance of a semi-active system, we consider both small pitching amplitudes and high pitching amplitudes, which we believe cover an adequately large range from low harvesting efficiencies to high harvesting efficiencies. Two representative pitching amplitudes $\theta_0 = 45°$ and $\theta_0 = 75°$ are investigated in detail.

2. Problem description and numerical methods

2.1. Kinematic motion of the foil

We consider a two-dimensional NACA0015 airfoil, as shown in Fig. 1. The chord length of the foil is *a*. The pivoting point is located at the center line of the foil with a distance *b* from the leading edge, which is one third of the chord length in this paper. The upstream flow velocity is denoted by *U*. The pitching angle is denoted by θ. The translational displacement of the pivoting point from the origin in $y-$ direction is *h*. The energy converting device is represented as a constant damping *c*. The foil performs combined motions of pitching and heaving, and the pitching profile is expressed as:

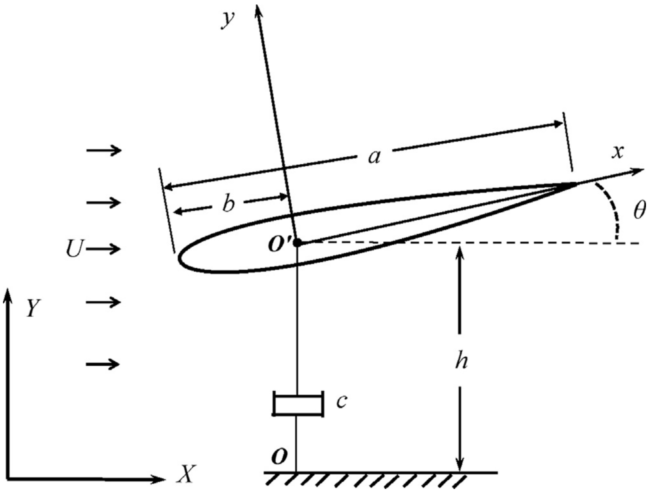

Fig. 1. Schematic of the energy harvester by a semi-active flapping foil.