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Influence of stroke deviation on the power extraction performance of a fully-active flapping foil

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ABSTRACT

The influence of stroke deviation on the power extraction performance of a fully-active flapping foil is numerically investigated in this work. A NACA0015 airfoil placed in a two-dimensional laminar flow is employed to extract power from the flow. It synchronously executes a rotational motion and a translational motion. In the traditional flapping foil based power extraction system, the foil only translates in vertical direction (heaving motion). In the current study, however, the foil can translate in both horizontal direction (surging motion) and vertical direction, which is attributed to the stroke deviation of a flapping wing. At a Reynolds number of 1100 and the position of the rotating axis at one-third chord, the effects of the amplitude of horizontal motion, the phase difference between the horizontal motion and the vertical motion as well as the frequency of horizontal motion on the power extraction performance are examined in detail. It is shown that compared with the traditional flapping foil, the efficiency improvement of power extraction for the flapping foil with additional horizontal motion can be achieved. Based on the numerical analysis, it is found that the enhanced power extraction from the vertical motion, which is induced by the increased lift force under appropriate horizontal motion, directly benefits the efficiency enhancement.

1. Introduction

With the rapid progress of modern technology, the global energy consumption has increased exponentially. Since the fossil fuel, which is not renewable, is declining, this situation motivates the development of alternative systems harvesting energy from renewable sources. In general, the natural resources, such as sunlight, wave, tides and wind, are the origin of renewable energy. Among them, tidal and wind energies have attracted increasing attention in recent years [1,2]. Conventionally, these energies can be harvested through turbine energy converters by rotating blades [3,4], which have been popularly employed in industry. Nevertheless, another type of energy harvesting systems by flapping foils has also been investigated recently. Compared with the rotary turbines, the flapping foil based energy harvesters can benefit from the low speed environment, which is appealing to utilize the exploitable tidal and wind resources [5].

Inspired by excellent hydrodynamics of aquatic animals and birds [6,7], the idea of harvesting energy via the flapping foils originates from the work of Wu [8]. In this study, it was denoted that a foil had to oscillate in an unsteady flow for the purpose of harvesting energy. Soon afterwards McKinney and DeLaurier [9] reported that the energy also could be harvested from a uniform flow. So far, there are three categories of models for the flapping foil based energy harvesting systems in terms of actuation mechanisms, i.e., fully-active systems, semi-active systems and fully-passive systems [10]. In the first type, the foil undergoes the imposed heaving and rotating motions without considering the actuation mechanism. In the second and third types, the foil executes the forced rotating and induced heaving motions and the self-sustained rotating and heaving motions, respectively.

To estimate the power extraction performance of a flapping foil, a quantitative parameter, i.e., power extraction efficiency, can be adopted. It is defined as the power extraction over the total power available in the oncoming flow passing through the swept area [11]. To achieve the efficiency improvement, a great deal of effort has been devoted and thus different techniques have been proposed. Examples include the use of a foil with corrugated surface [12] or deformable geometry [13], ground effect [14], auxiliary device [15,16], and multiple foils [17,18]. Besides, compared with the

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traditionally adopted sinusoidal motion profile, the efficiency also can be enhanced by modifying the motion trajectory. Xiao et al. [19] constructed a trapezoid-like rotating profile by tuning an adjustable parameter. With an optimal parameter, the maximal efficiency increases as high as 50% over sinusoidal profile. Later on, Lu et al. [20] investigated the influences of nonsinusoidal heaving profile as well as combined nonsinusoidal rotating and nonsinusoidal heaving profiles. They indicated that a square-like rotating profile together with a toothed-like heaving profile should be selected for the best power extraction performance (the output power coefficient can increase as high as 87.5% over sinusoidal profile). A similar work has also been performed by Ashraf et al. [21]. However, it should be pointed out that although the motion trajectory of a flapping foil has been changed in the studies mentioned above, the foil still oscillates vertically (transversely to the flow). To the best of our knowledge, no horizontal motion (parallel to the flow) is further taken into account yet for the purpose of power extraction.

On the other hand, besides rotating motion, both vertical and horizontal motions of a flapping foil are adopted in the application of locomotion [22–24]. In fact, this behavior is caused by the out-of-stroke-plane displacement of a wing (in which the wing tip deviates from the stroke plane according to some kind of motion pattern), or named as stroke deviation [25,26]. As a result, some typical wing trajectories are formed, which can be seen in bird flight. They include the flat stroke, the oval stroke, and the figure-of-eight stroke. Under specific flight conditions, the use of these motion trajectories can achieve high performance of hydrodynamics. Inspired by this fact, in this work, a motion profile involving rotation, heave (vertical motion) and surge (horizontal motion) due to stroke deviation is considered in a fully-active flapping foil based energy harvester. A NACA0015 airfoil, which is placed in a two-dimensional laminar flow, synchronously executes a rotational motion and a translational motion. Both the rotation and translation are sinusoidal. After selecting the Reynolds number and location of rotating axis, the effects of the surging amplitude, the phase difference between the heave and the surge as well as the surging frequency on the power extraction performance are numerically examined in detail. Based on the numerical results obtained, the influence of stroke deviation on the force behavior as well as the power extraction performance of the flapping foil is analytically demonstrated.

2. Problem description and methodology

2.1. Problem description

In this study, a NACA0015 airfoil is employed to represent an energy harvester. As displayed in Fig. 1, the foil in a uniform flow

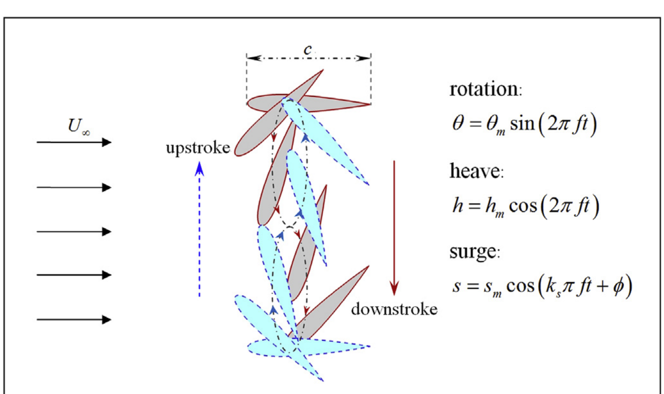

Fig. 1. Flow over a fully-active flapping foil performing rotation, heave and surge.

performs forced rotational and translational motions. Since the actuation mechanism is ignored in this type of systems, the power is completely extracted from the kinetic energy of flow.

Similar to the work of Kinsey and Dumas [11], an imposed sinusoidal mode is used to drive the foil. Thus, the governing equation is expressed as

$$\theta(t) = \theta_m \sin(2\pi ft),\ h(t) = h_m \cos(2\pi ft),\ s(t) = s_m \cos(k_s \pi ft + \phi) \quad (1)$$

where $\theta(t)$ is the instantaneous rotating angle at time t; θ_m is the rotating amplitude; $h(t)$ and $s(t)$ are the instantaneous displacements of the rotating axis along vertical and horizontal directions at time t, respectively; h_m and s_m are the corresponding heaving and surging amplitudes; f is the frequency of oscillation. Additionally, k_s is an adjustable parameter related to the surging frequency, and ϕ is the phase difference between the heave and the surge. In this study, the rotating axis is installed at one-third chord (it is a nice choice for power extraction [11]), and the rotating amplitude is chosen as $\theta_m = 75°$ (it is located in the range of high power extraction efficiency [11]). In addition, the heaving amplitude is fixed at $h_m/c = 1$ (it has greatly less effect on the performance of power extraction [11]), where c is the chord length of the foil. Moreover, the non-dimensional frequency (or reduced frequency) is defined as $f^* = fc/U_\infty$, where U_∞ is the free stream velocity. As the power extraction performance is only slightly improved when the flow changes from laminar to turbulent [11], the Reynolds number based on the free stream velocity and the chord length is selected as $Re = 1100$.

When the flapping foil works as an energy harvester, the instantaneous power extraction is the sum of power extracted from the heaving motion P_h, the surging motion P_s, and the rotating motion P_θ. Then, the overall power extraction P_o is computed by

$$P_o = F_L \frac{dh(t)}{dt} + F_D \frac{ds(t)}{dt} + M \frac{d\theta(t)}{dt} \quad (2)$$

where F_L and F_D are the lift and drag forces acting on the flapping foil, respectively, M is the torque about the rotating axis. Then, the overall power coefficient C_{op} can be calculated by

$$C_{op} = \frac{2P_o}{\rho_\infty U_\infty^3 c} = C_{p_h} + C_{p_s} + C_{p_\theta} = \frac{1}{U_\infty}\left[C_l \frac{dh(t)}{dt} + C_d \frac{ds(t)}{dt} + C_m \frac{d\theta(t)c}{dt}\right] \quad (3)$$

where C_l, C_d and C_m are the lift, drag and torque coefficients, respectively, ρ_∞ is the free stream density. Therefore, the time-averaged overall power extraction coefficient over one flapping period T can be computed by

$$\overline{C}_{op} = \overline{C}_{p_h} + \overline{C}_{p_s} + \overline{C}_{p_\theta} = \frac{1}{T}\int_0^T C_{op} dt \quad (4)$$

In an effort to further evaluate the efficiency of overall power extraction, the total power available in the oncoming flow passing through the swept area should be measured. It is defined as $P_a = \frac{1}{2}\rho_\infty U_\infty^3 d$, in which d is the maximum vertical displacement of the trailing edge of the flapping foil [11]. Then, the overall power extraction efficiency can be calculated by