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The time asymmetric pitching effects on the energy extraction performance of a semi-active flapping wing power generator

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HIGHLIGHTS

- A novel numerical coupling model for a semi-active flapping wing power generator is developed.
- Time asymmetric pitching motion power generator have better energy extraction performance than the conventional time symmetric one.
- Stronger vortices are observed around wing surface of the power generator with appropriate time asymmetric pitching.

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ABSTRACT

Inspired from the bird and insect's flight in nature, the time asymmetric pitching motion is proposed for the semi-active flapping wing power generator instead of conventional time symmetric pitching motion to seek better energy extraction performance. The NACA0012 wing, with prescribed pitching motion, is employed to represent as a power generator, where the vertical hydrodynamic force activates its heaving motion. A novel numerical coupling model is developed to simulate the interaction between the fluid and the semi-active power generator, and the effects of time asymmetric pitching on the energy extraction performance of the generator is analyzed. It is found that the time asymmetric pitching motion has a noticeable effect on the energy extraction performance of the generator, as it affects the instantaneous energy coefficient, energy efficiency and the flow structures. It is also concluded that with an optimal time asymmetric pitching motion, the maximal efficiency increases as high as 17% over the time symmetric pitching power generator.

1. Introduction

There has been attracted a lot of interests in the aerodynamic characteristics of the flapping wing because it not only has tremendous potential applications for flapping macro aero vehicle [1–3], but also for power generator [4–6]. Compared to traditional rotary turbines, the flapping wing power generator is believed to have many advantages such as simpler design, lower noise, higher efficiency and it is also more environmental friendly [7,8]. However, due to the complex flow around the power generator, a good understanding on the energy extraction characteristics is still of great importance for the successful design this system, and many researchers have focused on this issue.

Xiao et al. [9] performed a numerical study to investigate the motion trajectory influence on the energy extraction performance of a fully-active flapping power generator. They concluded that with an optimal parameter of the trapezoidal-like pitching motion, the maximal efficiency increases as high as 50% over sinusoidal profile power generator. Later on, a similar model was carried by Wu et al. [10] to study the ground effect on the power extraction performance of a power generator. It was found that compared to the situation in which there is no ground effect, the airfoil placed in close proximity to the ground gives improved power extraction performance, and the maximum efficiency improved by 28.6%. Le et al. [11] also employed a similar model to investigate the influence of wing kinematic and geometry on the power extraction performance of the power generator. They concluded that the efficiency is primarily dependent on the kinematics of the wing and secondly on the geometry. Unlike the traditional fully-active flapping wing power generator, Wu et al. [12] considered the effect of stroke deviation on the power extraction performance of a power generator, in which the wing could translate in both horizontal and vertical direction. They concluded that due to the stroke deviation the power extraction performance can be enhanced.

On the other hand, Zhu et al. [13] conducted a dual-model approach (a 2D thin-plate model and a 3D boundary-element

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model) to investigate the power extraction capacity of a semi-active power generator, in which the profile of the pitching motion was prescribed and the heaving motion was activated by the vertical hydrodynamic force. It was found that the performance of the system can be enhanced by the presence of a solid ground, as well as the thickness of the wing (at certain frequencies). Teng et al. [14] constructed a similar numerical model as Zhu et al. [13] to investigate the effects of no-sinusoidal pitching motion on energy extraction performance, and the results indicated that compared to the sinusoidal pitching motion system, the no-sinusoidal pitching motion is ineffective concerning the energy extraction performance. The numerical study by Shimizu et al. [15] concluded that the flapping wing power generator has an identical energy extraction performance as the present windmills at low tip-speed ratio region.

In summary, although there are lots of studies on the energy extraction performance of the flapping wing power generator, the kinematics of the fully-active or semi-active flapping power generator is just imposed time symmetric flapping. To the best of our knowledge, no time asymmetric flapping has further been taken into account yet for the purpose of designing flapping power generator. In fact, time asymmetric flapping is a common feature in real insect and bird flight [16–18], and it is believed that the time asymmetric flapping plays an important role in the energy extraction performance of the insect and birds' flight. In this paper, an investigation on the influence of the time asymmetric pitching motion of a semi-active power generator on its energy extraction performance is carried out. To solve the interaction of fluid and wing, a novel coupling numerical model was developed, then both the time symmetric and asymmetric pitching cases were computed, and the effect of time asymmetric on the fluid force, energy efficiency and vortex of the wing were analyzed details in the following.

2. Physical model and parameters definition

NACA0012 airfoil with chord length $d = 0.1$ m, is employed to represent the cross section of the wing. The pitching motion $\theta(t)$ of the flapping wing is prescribed, while the heaving motion $h\,(t)$ is activated by the vertical hydrodynamic force. The schematic of the wing motion is illustrated in Fig. 1, where $b = 0.25d$ is the pitching axis location, c is the damping coefficient which represents the energy extraction from the generator, K is the spring constant.

Different from the literature study, the pitching motion in this work is defined as time asymmetric:

$$\theta\,(t) = \int_0^t \omega\,(\tau)\,d\tau \tag{1}$$

$$\omega(t) = \begin{cases} \dfrac{\theta_m}{2\xi T}\pi\,\sin(\pi t/(\xi T)) & 0 \le t < \xi T \\ -\dfrac{\theta_m}{2(T-\xi T)}\pi\,\sin(\pi(t-\xi T)/(T-\xi T)) & \xi T \le t \le T \end{cases} \tag{2}$$

where T is the flapping period, θ_m is the amplitudes of pitching, ξ is the down pitching ratio which can be described by

$$\xi = \frac{t_{down}}{T} \tag{3}$$

where t_{down} is the time duration of down pitching in a flapping cycle.

Based on the Newton's second conservation law, the heaving motion of the wing is determined by:

$$M\ddot{h} + c\dot{h} + Kh = F_L \tag{4}$$

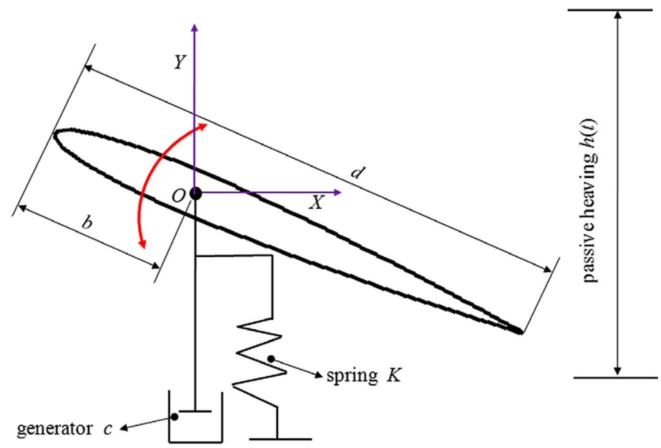

Fig. 1. The schematic of the wing motion.

where M is the mass of the wing, F_L is the lift force in Y direction as shown in Fig. 1. Generally, Eq. (4) should be described as dimensionless:

$$\ddot{h} + \frac{c}{M}\dot{h} + \frac{K}{M}h = \frac{F_L}{M}. \tag{5}$$

To clearly define the physical model, three dimensionless parameters are defined, named the Reynolds number Re, reduced frequency k, and density ratio ρ^*, respectively. They can be described as:

$$Re = \frac{U_\infty d}{\nu},\ k = \frac{fd}{U_\infty},\ \rho^* = \frac{\rho_s}{\rho} \tag{6}$$

where U_∞ is the free stream velocity, ν is the fluid kinematic viscosity, $f = 1/T$ is the flapping frequency, ρ the fluid density, ρ_s the wing density.

The energy extraction of the generator from the fluid can be defined as:

$$P_G = c\dot{h}^2, \tag{7}$$

and the energy which is needed to activate the pitching motion of the wing can be described as:

$$P_A = -M_T\omega \tag{8}$$

where M_T is the fluid torque of the wing.

Therefore the net energy of the generator from the fluid can be defined as:

$$P_T = P_G - P_A, \tag{9}$$

and the energy coefficient is described as:

$$C_P = \frac{P_T}{0.5\rho U_\infty^3 d}. \tag{10}$$

The mean energy coefficient when the generator reaches steady status can be calculated:

$$\overline{C_P} = \frac{1}{T}\int_t^{t+T} C_P dt, \tag{11}$$

and the energy extraction efficiency of the generator can be defined as:

$$\eta = \frac{\overline{P_T}}{0.5\rho U_\infty^3 h_{\max}} = \overline{C_P}\frac{d}{h_{\max}} \tag{12}$$

where h_{max} is the heaving amplitude which can be obtained after solving the interaction of the fluid and generator.