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Nonsinusoidal motion effects on energy extraction performance of a flapping foil

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ABSTRACT

To seek better energy extraction performance of a flapping hydrofoil, various nonsinusoidal motion profiles are employed instead of conventional sinusoidal flapping motions. The effects of nonsinusoidal motions are investigated for four kinds of nonsinusoidal flapping motions, i.e. varying effective angle of attack profile, nonsinusoidal pitching motion combined with sinusoidal plunging, nonsinusoidal plunging motion combined with sinusoidal pitching, and combined nonsinusoidal pitching and non-sinusoidal plunging motion. An adjustable parameters K is used to realize various nonsinusoidal profile varying from a sawtooth wave to a square wave profile. Numerical results show that by imposing a square-like effective angle of attack profile, extraction power and efficiency can be significantly increased compared with sinusoidal flapping motion. By accelerating the formation time and development of leading edge vortex (LEV), the square-like effective angle of attack profile leads to a better synchronization between the vertical force and plunging velocity. Similar effect on the flapping foil energy extraction performance is also found by imposing nonsinusoidal pitching profile. While the output power enhancement is quite limited by using the nonsinusoidal plunging profile. Moreover, the energy extraction performance can be significantly improved with an appropriate combination of nonsinusoidal pitching and nonsinusoidal plunging motion. Of all the nonsinusoidal motions studied, a toothed-like plunging profile together with square-like pitching profile should be selected for the best energy extraction performance.

1. Introduction

The continuous rise of world energy consumption and fuel prices motivates the development of alternative power extraction systems from renewable sources. Among the renewable energy originated from natural resources such as wave, sunlight, tides and hydro, power extraction from wind or tidal energy is an attractive alternative method. This extraction is generally accomplished by means of turbine energy converters which are based on the rotational motion of blades [1,2]. However, flapping foils (simultaneously pitching and plunging) are also capable of harvesting energy from vortices, free-surface waves, and uniform streams [3]. The application of flapping foils for energy extraction is inspired by the biological ability of animals, such as aquatic animals and birds, who exhibit excellent hydrodynamic or aerodynamic performance by extracting flow energy through their wing, tail or fin's flapping motion.

Flapping foil aerodynamics has been extensively studied by many researchers. However, much attention has been devoted to the propulsion performance of flapping foils [4–8]. The investigation into flapping foils for energy extraction is quite limited. Only in recent years has it become a focus of research [9–19]. The concept on the energy extraction behavior of an oscillating foil was initially proposed by McKinney and Delaurier [3] in 1981 and was further investigated by some researchers. McKinney and Delaurier [3] examined the feasibility of wind energy extraction through a combined pitching and plunging foil with analytical and experimental methods used. The results show that the output power was achievable and the efficiency was comparable to that of the rotational windmill. However, the full benefits of delayed stall and the associated LEV formation at high-pitch amplitudes were not fully exploited in their experiment.

Further, Jones and Platzer [9] systematically investigated the flapping foil aerodynamics with unsteady panel code coupled with a boundary layer algorithm employed. It is reported that at fixed

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Nomenclature

A	swept area of a flapping foil
c	foil chord length
C_M	momentum coefficient
C_P	power coefficient
C_{Ph}	power coefficient of plunging motion
C_{Phmean}	time-averaged power coefficient of plunging motion
C_{Pmean}	time-averaged power coefficient
$C_{P\theta}$	power coefficient of pitching motion
$C_{P\theta mean}$	time-averaged power coefficient of pitching motion
C_{Tmean}	time-averaged thrust coefficient
C_Y	lift coefficient
f	flapping frequency
H_0	nondimensional plunging amplitude
$h(t)$	plunging motion
k	reduced frequency ($k = 2\pi fc/U_\infty$)
K_e	nondimensional parameter used to realize different effective angle of attack profiles
K_h	nondimensional parameter used to realize different plunging profiles
K_θ	nondimensional parameter used to realize different pitching profiles
Re	Reynolds number
St	Strouhal number ($St = fA/U_\infty$)
t	physical time
T	flapping motion period
U_∞	free stream velocity
V_Y	plunging velocity
α_e	effective angle of attack
η	energy extraction efficiency
θ_0	pitching amplitude
$\theta(t)$	pitching motion

plunging amplitude and frequency, the flow would change from energy consumption to power extraction if the pitching amplitude was increased to a sufficiently high value. The power extraction didn't occur until the pitching amplitude exceeded the plunging induced angle of attack. Similar investigation into the boundary between energy consumption and power extraction regimes for flapping foil was also intensively presented by Kinsey and Dumas [10]. They mapped the power-extraction efficiency for an oscillating NACA0015 foil as a function of the frequency and pitching amplitude, and reported that motion-related parameters such as heaving amplitude and frequency have the strongest effects on foil performances, whereas geometry and viscous parameters turn out to play a secondary role. They also found that dynamic stall and the timing of the formation and shedding of a LEV during a flapping cycle play an important role in maximizing the power and efficiency. Furthermore, Jones et al. [11] demonstrated that the amount of harvested energy could be increased by using two foils in tandem formation. In this way the downstream foil could recover energy from the wake of the upstream foil. Similar tandem configuration was also conducted by Akhtar et al. [12] and Lehmann [13].

More recently, some researchers investigated the flapping foil for energy extraction with the actuated power required for activating the device taking into consideration. Shimizu et al. [14] optimized the system proposed by Isogai et al. [15] to maximize both the power and the efficiency. They conducted the multi-objective optimization of the flapping wing power generator, which was a concept that extracts wind energy via the aeroelastic response of an elastically supported rectangular foil. Following these, similar approaches were conducted by Zhu and Peng [16,17], who examined the physical process of energy extraction from a uniform flow through the coupling between pitching and plunging modes of a flapping foil using a fluid–structure interaction model based upon Navier–Stokes solver. In their approach the pitching motion of the foil was prescribed to induce unsteady time-dependent forces and moments for foil plunging motion, which was utilized for energy extraction. However, only at low oscillating frequency a positive net energy extraction was observed.

Of all the foils in the above studies, without exception, oscillates in sinusoidal profile, as it is one of the simplest harmonic profiles. Little attention has been paid to the effects of nonsinusoidal motion on energy extraction performance of a flapping foil. In the numerical analysis of an oscillating foil for wind and hydropower generator by Ashraf et al. [18], an alternative nonsinusoidal foil motion was used. The foil plunge was maintained for as long as possible at a high velocity and followed by rapid pitching reversals. It is reported that the results for a NACA0014 foil undergoing nonsinusoidal pitch-plunge motion indicates around 17% increase in power generated and around 15% increase in efficiency over that for sinusoidal motion. However, they didn't consider the effect nonsinusoidal pitching profile or plunging profile separately and no attempt was made to study the effect of effective angle of attack (AOA) profile. In the numerical study by Xiao et al. [19], a nonsinusoidal trajectory was constructed by combining a specially proposed trapezoidal-like pitching motion with a sinusoidal plunging motion. A significant increment of output power was obtained for trapezoidal-like pitching motion over a certain range of St (Strouhal number). However, no attention was paid to the effect of nonsinusoidal plunging profile, combined nonsinusoidal pitching and nonsinusoidal plunging profile or effective AOA profile. The effect of toothed-like motion profiles was also lacking in the work of Xiao et al. [19].

The purpose of this paper is to systematically evaluate and quantify the effects of various nonsinusoidal motions on the flapping foil energy extraction performance, and to determine whether the output power can be improved by these methods. The effects of effective AOA profile, nonsinusoidal pitching profile, nonsinusoidal plunging profile, combined nonsinusoidal pitching and nonsinusoidal plunging profile are investigated. Computations are conducted for a 2D NACA0012 flapping foil with both toothed and square-like oscillating profiles applied.

2. Numerical method

2.1. Solver

The unsteady flow field around the foil section is simulated using the CFD package CFX 13.0, with an unsteady incompressible solver. A second-order-accurate backward implicit scheme is used for time discretization. To discretize convection and diffusion terms, High Resolution Scheme is used, which is a bounded second-order upwind biased discretization giving second-order-accurate gradient resolution while keeping solution variables physically bounded [20]. The dynamic flapping motion is achieved by using a CFX expression language (CEL) subroutine developed and attached to the CFX solver.

Two zones of grids with a sliding grid interface are used and a no-slip boundary condition is applied along the foil surface. The far-field boundary is set to at least 35 chords from the foil such that the