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How motion trajectory affects energy extraction performance of a biomimic energy generator with an oscillating foil?

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ABSTRACT

A non-sinusoidal trajectory profile is proposed for the oscillating hydrofoil in the energy generators instead of conventional sinusoidal plunging/pitching motions to seek better energy extraction performance. The novel profile is achieved by combining a specially designed trapezoidal-like pitching motion with a sinusoidal plunging motion and investigated numerically on its output energy coefficient and total output efficiency. Through an adjustable parameter β, the pitching profile can be altered from a sinusoidal ($\beta = 1.0$) to a square wave ($\beta \to \infty$). In this work, a series of β ranging from 1.0 to 4.0 are investigated to examine the effect of combined motion trajectory on the energy extraction performance. The study encompasses the Strouhal numbers (*St*) from 0.05 to 0.5, nominal effective angle of attacks α_0 of 10° and 20° and plunging amplitude h_0/c of 0.5 and 1.0. Numerical results show that, for different β pitching motions, a larger α_0 always results in a higher extraction power C_{op} and total efficiency η_T. Compared with the sinusoidal motion ($\beta = 1$), significant increment of C_{op} and η_T can be observed for $\beta > 1$ over a certain range of *St*. The investigation also shows that there exists an optimal pitching profile which may increase the output power coefficient and total output efficiency as high as 63% and 50%, respectively, over a wide range of *St*. Detailed examination on the computed results reveal that, the energy extraction performance is determined by the relative ratio of the positive and negative contributions from the different combination of lift force, momentum and corresponding plunging velocity and pitching angular velocity, all of which are considerably affected by β.

1. Introduction

The use of renewable energy, originated from natural resources such as wave, sunlight, tides and hydro, is being extensively explored. Among these renewable energies, marine current stream and tidal energy show a number of merits over others as it is predictable unlike wind energy being respondent to the random effects of weather system [1].

Tidal current energy is conventionally extracted through the deployment of turbine energy converters which are based on the rotational motion of blades [1,2]. In the past decade, marine current turbines have been growing up to a major industry, with a number of turbine farms having been constructed. The erection of these fixed marine turbine farms in ocean [2], however, has encountered some criticism for the supposed impact that they have on the environment, for example, they take up excessive amounts of space, become a danger to local wildlife, and require an average velocity of 5–7 knots to be financially viable, while the vast majority of currents flow at lower speeds [3].

In nature, many animals (aquatic animals, insects and birds) exploit energy directly from the fluid around them by controlling and maneuvering their bodies' locomotion via oscillation mechanism either actively and/or passively [4]. For example, tuna, dolphin and shark exhibit excellent hydrodynamic performance with high cruising speed, high efficiency and low noises by extracting water energy through their tail and/or fin's flapping motion. Recently, inspired by this biological ability, a new class of energy-harvesting prototype typified with unsteady, oscillation motions has been developed [2,3,5,6]. Notable examples are an oscillating marine current energy converter [3,5] and a flutter windmill [6] for wind

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energy harness. In principle, the water/wind kinetic energy is extracted to the mechanical energy and then transformed into electricity by the oscillation motion of device components, which imitates the propulsion and energy extraction mechanism adopted by the animals through the flapping motions of their tails, fins or wings. A schematic diagram for a typical energy extraction device based on a flapping wing is shown in Fig. 1. The rapid development of such devices has sparked the interest in understanding of their underlying fundamental aero/hydrodynamics.

The research on the hydro/aero behavior of oscillating based energy extraction phenomena is in its infancy although the concept can be dated back to 1981 [7]. Compared to its counterpart on oscillating propulsion [8–12], the study on flapping foils for energy extraction is very limited. Only in the past few years, the energy harness mechanism behind the oscillating foil has gradually attracted attention [13–20].

In the pioneer study by McKinney and DeLaurier [7], the ability of a harmonically oscillating wing, through combined pitching and plunging motions, to extract wind energy was investigated. It was shown that the output power was achievable and the efficiency was comparable to that of the rotational windmill. An earlier work was conducted by Davids [13] using experimental measurements and unsteady panel method. His numerical study on a NACA0012 foil showed that the total efficiency of energy extraction could be as high as 30% with optimized combination of plunging amplitude and frequency. Subsequently, Jones et al. [14,15] carried out a systematic numerical investigation by using an unsteady panel code coupled with a boundary layer algorithm. Their parametric studies covered a series of parameters ranging from thrust generation propulsion to power extraction. Given the fixed plunging amplitude and frequency, it was found that, if the pitching amplitude was increased to a sufficiently high value, the flow would change from energy consumption to power extraction. With various combinations of pitching and plunging, the condition for power extraction occurrence is that the pitching amplitude must exceed the plunging-induced angle of attack (AOA). A recent computational effort by Kinsey and Dumas [16] presented a mapping of power-extraction efficiency for an oscillating NACA0015 airfoil in the frequency and pitching amplitude domain. Through unsteady laminar-flow simulations using the commercial code FLUENT, they observed that, the maximum efficiency could go up to 34% with a foil plunging with one chord amplitude and pitching around one third of the chord within the domain of $0 < fc/U_\infty < 0.25$ and $0 < \theta_0 < 90^\circ$. Here f is the oscillating frequency, c is the chord length, U_∞ is the far-stream velocity and θ_0 is the pitching amplitude.

An experimental investigation on a flapping foil was more recently conducted by Simpson et al. [17] By force/load measurement, they investigated the impact of Strouhal number ($St = fA/U_\infty$, where A is the swept area of a flapping foil), maximum angle of attack, and aspect ratio on the power extraction efficiency of a NACA0012 foil. A maximum of hydrodynamic efficiency at 43% was found at the aspect ratio of 7.9, the Strouhal number of 0.4 and the maximum angle of attack of 34.37° with the phase angle difference of 90° between pitching and plunging.

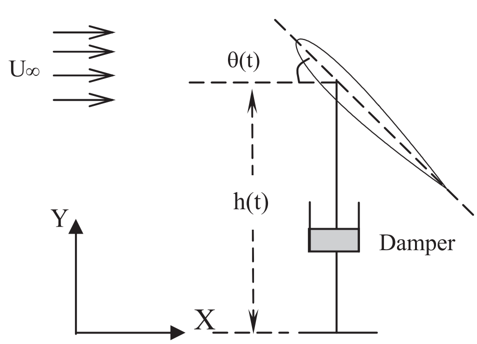

Fig. 1. A schematic diagram for a typical oscillating energy extraction device. (The damper represents the device of energy accumulation and storage, which is not considered yet in the present work.)

Whilst some insights have been gained with these studies, by prescribing the pitching and plunging oscillation motions, the above numerical modeling decouples the interaction between oscillating device and its surrounding fluid. Therefore, they are concentrated on the hydrodynamic power only without taking into account the actuated power required for activating the device, which must be addressed by the coupled computation with fluid and dynamic response of device. Recently, some attempts have been made on this aspect [13–15]. Zhu and Peng [18,20] numerically studied, by using a Navier–Stokes solver, a novel approach to extract energy. In their approach, the pitching motion of the foil was prescribed, whilst the heaving motion, triggered by the unsteady time-dependent forces and moments induced by the oscillating pitching, was utilized for energy extraction. A positive net energy extraction was noted possibly only at low oscillating frequency. Similar approaches and results were obtained by Shimizu et al. [21] for the flapping wing study with its application in wind energy utilization.

Given the prescribed motion approach, it is worthy to note that, the foil in the above studies oscillates with no exception from sinusoidal plunging/pitching, as it is one of the simplest harmonic profiles. An interesting phenomena observed by previous research on propulsion foil [8–12] reveled that, under the condition of combined sinusoidal pitching/plunging, the climbing-up trend for thrust coefficient (C_t) and input power coefficient (C_{ip}) against St stops at a sufficiently high St and starts to diminish rapidly with further increasing St. This is strongly linked to the degradation of effective AOA (α_{eff}) from sinusoids at higher St. As we will show later, the similar behavior is observed on the output power coefficient (C_{op}) for the energy extraction case. As for the propulsion case, efforts were made initially by Hover et al. [10] through experiments, where α_{eff} was forced to be a cosine and then the plunging motion was derived. The propulsion performance was shown to be evidently improved at certain maximum effective angle of attack α_{max}. The derived plunging motion in such a case, however, becomes non-sinusoidal. A recent numerical attempt by Xiao and Liao [11] observed the similar tendency by modifying either pitching or plunging motion from a sinusoid. The computations also showed that the pitching modification yielded even better performance than that from the plunging adjustment. Such a phenomenon motivates us to investigate whether the power extraction performance of oscillating foil can be improved by replacing sinusoidal motions with non-sinusoidal oscillations.

In the present work, a non-sinusoidal trajectory is constructed by combining a specially proposed trapezoidal-like pitching motion with a sinusoidal plunging motion. By tuning an adjustable parameter β, one can gradually change the designed pitching profile from a sinusoid ($\beta = 1.0$) to a square wave ($\beta \to \infty$). This study is therefore concentrated on how motion trajectory affects power extraction performance. Computations will be conducted for a NACA0012 oscillating foil with a series of β values along with different oscillating frequency (f) and effective angles of attack α_{eff}.

2. Computational approach

2.1. Numerical method

In this study, time-dependent viscous flows around an oscillating NACA0012 foil for energy extraction purpose are simulated