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Energy harvesting performance and flow structure of an oscillating hydrofoil with finite span

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ABSTRACT

The energy harvesting performance and resulting flow structures of a hydrofoil oscillating in pitch and heave are studied experimentally in a water flume. The shape of a hydrofoil cross-section is shown to have negligible influence on the power generation for the geometries tested. It is found that contribution to efficiency from heaving motion increases with reduced frequency at optimal pitching amplitude. However, contribution to efficiency from pitching motion decreases with reduced frequency because the development of a leading-edge vortex during the stroke is delayed at the high reduced frequency. Increasing the aspect ratio of the hydrofoil leads to a higher contribution to efficiency from heaving over the range of aspect ratios considered in this study. However, the effect of the aspect ratio on efficiency from pitching is negligible. When end plates are mounted at both ends of the hydrofoil, heaving power enhances. However, the enhancement of heaving power becomes smaller with increasing aspect ratio. Meanwhile, pitching power improves uniformly with the addition of end plates for all three aspect ratios. Our study suggests that the dependence of energy harvesting performance on aspect ratio is due to the delayed growth of the leading-edge vortex near the ends of the hydrofoil.

1. Introduction

Energy harvesting from flowing water such as ocean and tidal currents has emerged as a promising renewable energy resource, and research and development in this field is on the rise. Most of hydrokinetic energy harvesting technologies have been based on vertical-axis or horizontal-axis rotary turbines. As an alternative to rotary turbines, hydrokinetic energy harvesting using an oscillating hydrofoil has recently received increased attention, and some hydrofoil prototypes have been designed and tested (Kinsey et al., 2011; Young et al., 2014; Xiao and Zhu, 2014). Unlike horizontal-axis rotary turbines, which rely solely on steady force generation, the pitching and heaving hydrofoil employs an unsteady force generation mechanism (Kinsey and Dumas, 2008; Zhu and Peng, 2009). When the hydrofoil pitches up at a high angle of attack, a "dynamic stall" vortex is created at the leading-edge of the hydrofoil. Because of the low pressure on the upper suction surface created by the leading-edge vortex, the hydrofoil can generate a large heaving force. However, as the leading-edge vortex separates from the hydrofoil and moves downstream, the heaving force decreases quickly and in order to maximize power production, the hydrofoil should rotate, changing the sign of its pitch angle, and begin to heave in the opposite direction, creating another leading edge vortex. This periodic pitching and heaving motion can efficiently extract energy from the kinetic energy of a fluid flow and is also used as one of the unsteady propulsion mechanisms in the

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Nomenclature

c	Hydrofoil chord	f	Oscillation frequency
s	Hydrofoil span	f^*	Reduced frequency (fc/U_∞)
U_∞	Free-stream velocity	T	Oscillation period
AR	Aspect ratio (s/c)	t^*	Non-dimensional time (t/T)
A_s	Full swept area of the leading edge	F	Heaving force
d	Distance from the hydrofoil to the edge of the end plate	M	Pitching torque
h	Heaving position	C_F	Heaving force coefficient ($2F/\rho U_\infty^2 A_s$)
h_0	Heaving amplitude	C_M	Pitching torque coefficient ($2\,M/\rho U_\infty^2 c A_s$)
θ	Pitching angle	P	Power ($Fh + M\theta$)
θ_0	Pitching amplitude	η	Total efficiency ($2\overline{P}/\rho U_\infty^3 A_s$)
α_e	Effective angle of attack	η_h	Heaving efficiency ($2\overline{Fh}/\rho U_\infty^3 A_s$)
		η_p	Pitching efficiency ($2\overline{M\theta}/\rho U_\infty^3 A_s$)
		ω	Spanwise vorticity
		Γ_{nd}	Non-dimensional circulation ($\lvert\int \omega \mathrm{d}A\rvert/U_\infty c$)

flapping locomotion of animals (Maxworthy, 1979; Ellington, 1996).

The oscillating hydrofoil technology has several advantages over the conventional turbine technology (Xiao and Zhu, 2014). The maximum blade speed of the hydrofoil is several times lower than the blade tip speed of a conventional turbine at optimal operation, which may reduce harmful interactions with aquatic animals. In addition, the device is structurally more robust because it does not rely on the fast rotation of long blades. Since the hydrofoil can be designed to have a high aspect ratio, it is also advantageous in operation in shallow water channels where the velocity of tidal currents is high (Franck et al., 2015).

The study of energy extraction using flapping foils was pioneered by Birnbaum (1924). The analytical and experimental study of McKinney and DeLaurier (1981) showed that the flapping foil could extract energy and its efficiency was comparable to rotary turbines. In the last several years, researchers have investigated the relationship between operational parameters, resulting flow structures, and overall energy harvesting performance. Jones and Platzer (1997) numerically studied the pitching-only, heaving-only, and combined motions of the power-extracting foil over a broad parameter space. Simpson et al. (2008) conducted an experimental parametric study on the influence of the reduced frequency ($f^* = fc/U_\infty$ where f is the operating frequency, U_∞, the freestream velocity, and c, the hydrofoil chord), the maximum effective angle of attack (α_e) and the hydrofoil aspect ratio ($AR = s/c$ where s is the hydrofoil span) on energy harvesting performance. Through a computational parametric study of the frequency and pitching amplitude domain, Kinsey and Dumas (2008) showed that energy conversion efficiency could be as high as 34%. By investigating the relationship between wake stability and efficiency, Zhu (2011) proposed a reduced frequency, f^*, of about 0.15 for optimal performance. With a passive heaving motion induced by an imposed pitching motion, high efficiency was achieved by controlling the interaction between the flapping foil and the leading-edge vortex (Zhu and Peng, 2009).

In order to improve energy extracting performance of the oscillating foil, several ideas have been proposed. It has been reported that efficiency increased when a trapezoid-like pitching motion with a sinusoidal heaving motion was used instead of sinusoidal pitching and heaving motions (Ashraf et al., 2011; Xiao et al., 2012). A corrugated foil inspired by a scallop shell enhanced efficiency by 6% as compared to the NACA0012 foil in the same conditions (Le et al., 2013). When the foil was placed either near a solid wall or between two parallel plane walls, it generated more power than the foil in an unconfined flow (Wu et al., 2014). A flexible foil could enhance efficiency by increasing the peaks in lift force over a flapping cycle (Liu et al., 2013). The foil with a deformable tail also improved efficiency compared to a foil with a rigid tail (Wu et al., 2015). It was also found that, in a streamwise tandem configuration of the foils, favorable interaction between the downstream foil and the wake vortices could lead to high power extraction (Kinsey and Dumas, 2012a). Energy harvesting for the tandem configurations was also studied experimentally and computationally by Fenercioglu et al. (2015a) and Karakas and Fenercioglu (2016). In addition, by placing side walls, the foil in confined flow could outperform the highest efficiency case in free flow (Karakas et al., 2016).

Despite the extensive reports regarding energy harvesting hydrofoils, most of the studies have been conducted using two-dimensional numerical simulations, and there have been few studies on the three-dimensional effects of a hydrofoil with finite span in spite of its importance in practical applications. The experimental work of Simpson et al. showed that the efficiency of the foil increased with aspect ratio (Simpson et al., 2008). The computational work of Kinsey and Dumas found that, compared to its 2D equivalent, average power extracted from a three-dimensional foil dropped by 20%–30%, and the end plates attached to both ends of the hydrofoil could recover some of this loss (Kinsey and Dumas, 2012b). However, these studies focused solely on the efficiency trends with different aspect ratios rather than providing any detailed analysis on the leading-edge vortex dynamics and its relation to hydrofoil performance.

Most, if not all, of the previous studies have considered airfoil-derived geometries such as the NACA0012. The use of flat plates instead of airfoils was first introduced by Semler (2010) and Platzer et al. (2011). Given that the key to oscillating hydrofoil performance is the formation and capture of a strong leading-edge vortex, one might suspect that a classically shaped airfoil, which is designed to mitigate separation effects, may not necessarily be optimal and is certainly unlikely to be required. Furthermore, a simple geometry would be extremely attractive from the perspective of manufacturing and maintenance costs associated with an energy harvesting system. For this reason, it is desirable to closely examine the effect of various hydrofoil cross-section geometries on device performance, with a focus on the leading-edge shape.

With these issues in mind, the present work extends this body of literature in several important ways. Firstly, we provide much