Flow energy harvesting based on oscillating passively-deforming airfoils

Firas F. Siala†

Department of Mechanical Engineering, Oregon State University, Corvallis, OR 97331, USA

1. Introduction

The rising global trend to reduce dependence on fossil fuels has provided significant motivation toward the development of alternative energy conversion methods and new technologies to improve their efficiency. Recently, the idea of using oscillating airfoils has been gaining a wider scope of attention as a means of extracting kinetic energy from streams, rivers, tidal flows and wind (Xiao & Zhu 2014). A large contribution to the existing knowledge has come through the studies of animal flight and swimming (Drucker & Lauder 1999; Triantafyllou *et al.* 2000; Sane 2003; Ho *et al.* 2003), where the oscillatory/flapping motion of wings or fins are used to achieve high propulsion efficiency and maneuvering.

The concept of flow energy harvesting using oscillating airfoils was first proposed by McKinney & DeLaurier (1981). The motion kinematics of the oscillating airfoil, which is typically modeled as combined heaving and pitching motion at very large angles of attack, results in flow separation and formation of leading edge vortices (LEVs). LEV structures are exploited by oscillating airfoils to attain high energy harvesting efficiency values. This is in contrast to the conventional rotary turbines, where the flow around the blades must remain fully attached to the surface to achieve high efficiency levels. Preliminary studies show that oscillating airfoil energy harvesters are capable of extracting energy with efficiency comparable to rotary devices Kinsey & Dumas (2008); Zhu (2011); Young *et al.* (2014). Furthermore, there are several prominent features of oscillating airfoil energy harvesters compared to the conventional turbines: (i) they are environmentally friendly in terms of noise generation due to their relatively low tip-speed, thus reducing impact on the navigation of flying/swimming animals; (ii) without the centrifugal stress associated with rotating blades, the oscillating devices are structurally robust; and (iii) oscillating devices sweep through a rectangular cross section of the flow, and therefore the swept area of a single airfoil can be wide and shallow, allowing large systems to be installed in shallow water (Zhu 2011). With the rapid development of such devices (industry is already involved in developing full-scale prototypes), the knowledge of their underlying fluid dynamics is required to improve the efficiency of existing devices. In particular, there is a need to thoroughly understand the spatio-temporal evolution of the flow around the oscillating airfoil, in order to develop mechanisms to control the LEV dynamics that will lead to improved energy harvesting performance.

2. Background and Research Objectives

The kinematics of an oscillating airfoil energy harvester consist of combined sinusoidal heaving (h) and pitching motion (θ):

$$h = h_0 sin(2\pi f t) \tag{2.1}$$

† Email address for correspondence: sialaf@oregonstate.edu

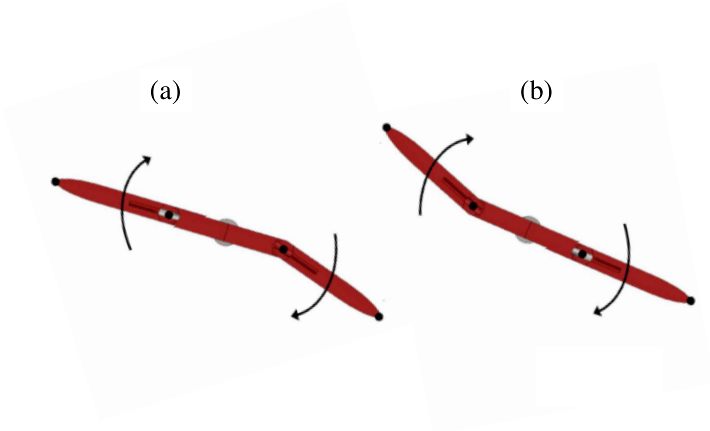

FIGURE 1. Illustration of airfoil surface deformation during upward pitching motion. (a) Trailing edge deformation and (b) leading edge deformation.

$$\theta = \theta_0 sin(2\pi f t + \Phi) \tag{2.2}$$

where h_0 is the heaving amplitude, θ_0 is the pitching amplitude, f is oscillation frequency, Φ is the phase-shift between heaving and pitching and t is time. The instantaneous power extracted by an oscillating airfoil can be defined as follows:

$$P = F_y\dot{h} + M_z\dot{\theta} \tag{2.3}$$

where F_y is the lift force, M_z is the pitching moment, $\dot{h}$ is the heaving velocity and $\dot{\theta}$ is the pitching velocity. The power extraction efficiency, η, is defined as the ratio of the time-averaged power extracted ($\overline{P}$) to the total power available in the incoming flow passing through the swept area:

$$\eta = \frac{\overline{P}}{1/2\rho U_\infty^3 A} \tag{2.4}$$

where ρ is fluid density, U_∞ is the free stream velocity and A is the area swept by the oscillating airfoil. From Eq. 1.3, it can be seen that there are two main factors influencing the power output: (i) the magnitude of the lift force F_y and aerodynamic moment M_z and (ii) the correlation between F_y and $\dot{h}$ as well as between M and $\dot{\theta}$. Several studies have been conducted in the past that investigate different mechanisms that enhance both the force magnitude as well as the correlation between the force and motion (Xiao & Zhu 2014). One prominent mechanism to enhance the power extraction and efficiency is the use of deforming airfoils. Previous studies on insect wings as well as fish fins suggest that a certain degree of deformation near the trailing edge may lead to the generation of higher thrust and lift forces. This is attributed to the manipulation of the LEV generation, and force reorientation associated with the deformations of the surface (Zhao *et al.* 2011; Nakata *et al.* 2011; Nakata & Liu 2012). Furthermore, Liu *et al.* (2013) have shown through using prescribed airfoil deformation, that surface flexibility near the leading and trailing edges of the airfoil can alter the timing of peak force and magnitude, respectively.

While there are numerous numerical-based studies on oscillating airfoil energy harvesters, there is a lack of experimental data that can be used for validation and exploring new physical phenomena. One of the main experimental challenges is in the direct transient force measurements, which is often unfeasible for highly unsteady aerodynamic flows. Unsteady aerodynamic flows indicate that the time scale of airfoil motion is smaller

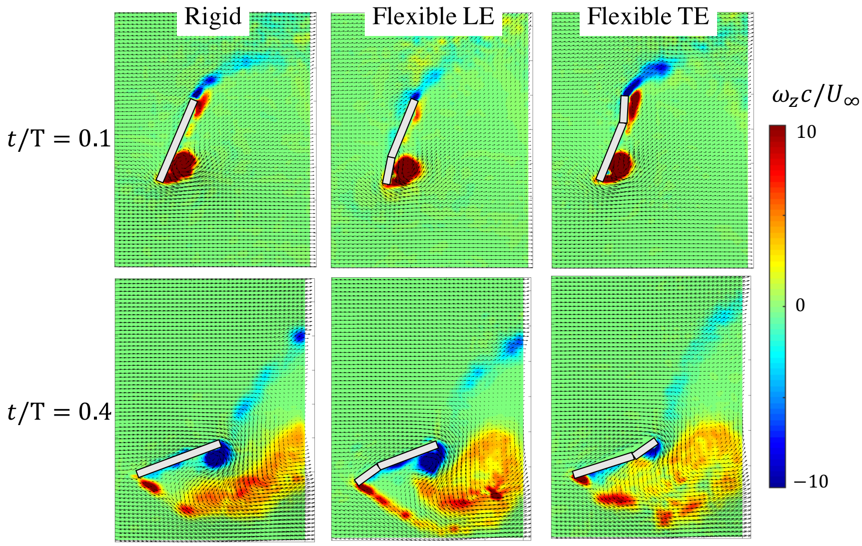

FIGURE 2. Vorticity and velocity fields for rigid, flexible LE and flexible TE airfoils at $t/T = 0.1$ and $t/T = 0.4$. The large, counter-clockwise rotating red-colored vortex structure represent the LEV and the clockwise rotating blue vortices that form at $t/T = 0.4$. represent the trailing edge vortices (TEVs).

than the time scale of the flow, where the degree of unsteadiness is often described by the reduced frequency ($k = fc/U_\infty$, where c is airfoil chord length). The difficulty in measuring transient forces of highly unsteady airfoils is due to the inertial forces growing rapidly at high oscillation frequencies (proportional to f^2), whereas the aerodynamic forces grow with U_∞^2. In fact, in the range of reduced frequencies relevant to efficient energy harvesting performance ($k = 0.1 - 0.2$), the inertial forces become at least an order-of-magnitude larger than the aerodynamic forces, and therefore the accuracy of the force measurements becomes unreliable.

The objectives of this work are as follows: (i) experimentally investigate the energy harvesting performance of an oscillating airfoil, (ii) develop a reduced-order model to estimate the aerodynamic forces and energy harvesting performance and (iii) develop a flow-control mechanism that enhances the energy harvesting performance. Our performance enhancing mechanism is based on the use of bio-inspired deforming airfoils. However rather than using prescribed deformation, we use passive airfoil deformation at the leading and trailing edges. An illustration of the deforming airfoil during the oscillation cycle is shown in Fig. 1. The passive deformation is established by inserting a torsion rod into a slot along both the driven airfoil body and leading/trailing edge, forming a hinge. The rod is secured at one end to the airfoil body and the other end to the leading/trailing edge, providing a means to allow rotation of the leading/trailing edge controlled by the torsion characteristics of the rod material. When the airfoil is set in motion, the leading/trailing edge passively actuates which provides dynamic changes of the effective angle of attack during the heaving and pitching cycle.

3. Results

The experiments were conducted in a closed-loop wind tunnel at Oregon State University. A motion device was built to generate the coupled sinusoidal heaving and pitching

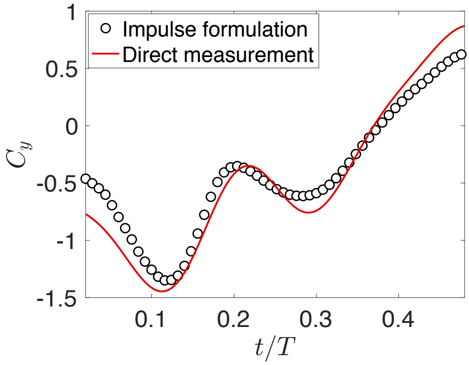

FIGURE 3. Comparison of the transient lift coefficient for $k = 0.08$ obtained from the impulse formulation with the results obtained from direct force measurements; results are given for the half cycle beginning when the foil is at the top heaving position.

motion. The motion device is equipped with load-cells that measure the aerodynamic forces. Furthermore, the flow field around the oscillating airfoil was obtained using particle image velocimetry (PIV) (Adrian & Westerweel 2011). Examples of the measured velocity and vorticity fields for a rigid, flexible leading edge (LE) and flexible trailing edge (TE) airfoils are shown in Fig. 2 for two different times during the oscillation cycle.

Since the flow is dominated by large vortex structures, it is ideal to describe aerodynamics forces and power performance in terms the dynamics of these structures. Noca (1996) has shown that it is possible to derive an equation that represents the transient forces in terms of the dynamics of these vortical structures. That being said, his formulation contains complicated boundary integral terms with unclear physical meanings, which makes it difficult to identify mechanisms responsible for efficient energy harvesting process. In our work, we have shown that the force equation developed by Noca (1996) can be significantly reduced to the following equation:

$$\mathbf{F} \approx -\rho \frac{d}{dt} \int_{CV} \mathbf{x} \times \boldsymbol{\omega} dA + \rho \int_{CV} \mathbf{u} \times \boldsymbol{\omega} dA \tag{3.1}$$

where $\mathbf{x}$ is the position vector measured, $\boldsymbol{\omega}$ is the vorticity vector and $\mathbf{u}$ is the velocity vector. Note that in order to obtain this reduced force equation, the origin of the position vector must be located anywhere along the downstream boundary of the control volume (for more information, see Siala (2019)). Both terms in Eq. 3.1 are evaluated over the entire control volume (CV). The first term represents the rate of change of the vortex impulse. It can be shown that the rate of change of the vortex impulse is related to the rate of growth of the vortical structures (e.g. the LEV), as well as their advection velocity along the airfoil. The second term is known as the vortex force, and it can be thought of as a history effect of the vortices that have already been shed from the airfoil. All the variables shown in Eq. 3.1 are easily obtained from PIV measurements. A comparison of the lift force coefficient obtained using the impulse formulation with direct transducer-based measurements for $k = 0.08$ is shown in Fig. 3. As can be seen, our impulse formulation can predict the lift force coefficient quite well. Similarly, a reduced vortex impulse-based equation for the aerodynamics moment can be derived:

$$\mathbf{M} \approx \rho \frac{1}{2} \frac{d}{dt} \int x^2 \boldsymbol{\omega} dA + \rho \int \mathbf{x} \times (\mathbf{u} \times \boldsymbol{\omega}) dA - \rho \frac{1}{2} \oint x^2 \mathbf{n} \times (\mathbf{u} \times \boldsymbol{\omega}) dS \tag{3.2}$$

where $\mathbf{n}$ is a unit normal vector pointing away from the fluid. Note the the last term of Eq. 3.2 is evaluated over the control volume surface S.

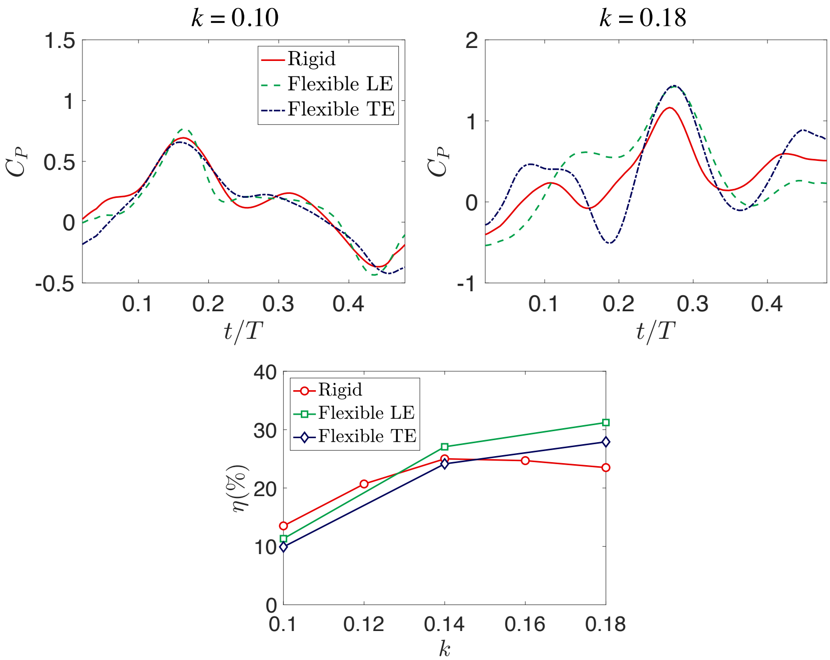

FIGURE 4. Top row: power coefficient for $k = 0.10$ and $k = 0.18$ versus time. Bottom row: energy harvesting efficiency versus reduced frequency. The results are shown for rigid, flexible LE and flexible TE airfoils.

Using the force and moment equations, the instantaneous power can now be calculated using Eq. 2.3. The results are shown in Fig. 4 for the rigid, flexible LE and flexible TE airfoils. The results are shown for $k = 0.10$ and $k = 0.18$. Also shown in Fig. 4 is the energy harvesting efficiency as a function of reduced frequency k. For low k values, it is shown that airfoil deformation at the leading and trailing edges have negative effects on the performance. As k is increased, the benefits of deforming airfoils become apparent, where the energy harvesting efficiency increases from 22% for a rigid airfoil to 29% and 32% for flexible TE and LE, respectively, at $k = 0.18$. We have determined that the flexible LE enhances the rate at which the LEV grows by increasing the strength of the shear layer that feeds the LEV with vorticity. On the other hand, the flexible TE airfoil enhances the performance by introducing a camber to the airfoil that results in increasing the strength of the LEV. Using the impulse-based force equations, we can see that increasing the strength and/or the rate of change of vorticity of the LEV results in greater force and moment generation, and thereby greater power coefficients.

4. Significance, Impact and Future Directions

In this work, we conducted extensive wind tunnel testing and theoretical analysis to study the effects of deforming surfaces on the energy harvesting performance of oscillating airfoils. The flow field around the oscillating airfoil is captured using particle image velocimetry (PIV). Using the data obtained from PIV measurements, we developed a reduced-order model of the aerodynamic force and moment that can easily describe the effects of vortical structures on the energy harvesting performance. We have shown that deforming airfoil surfaces can increase the energy harvesting efficiency by as much as 45%.

The topic of oscillating energy harvesters is still a relatively new field of research. Our results provide the first set of extensive experimental data of the flow field of oscillating energy harvesters. The reduced-order impulse-based force and moment equations directly show how to manipulate vortex structures such as the LEV to enhance the performance. Therefore, researchers may use our model as a framework for designing future-generation performance enhancing mechanisms.

5. Scholar Contributions

Journal Publications:

FF Siala and JA Liburdy, "Leading edge vortex dynamics and impulse-based lift force analysis of oscillating airfoils". *Experiments in Fluids, under review.*

FF Siala and JA Liburdy, "Power estimation of flapping foil energy harvesters using vortex impulse theory". *Renewable Energy, under review.*

FF Siala, K Kamrani, N Vickie and JA Liburdy, "Experimental study of inertia-based surface deformation of oscillating airfoil energy harvesters". *In preparation for submission.*

AD Totpal, **FF Siala** and JA Liburdy, "Energy harvesting of an oscillating foil at low reduced frequencies with rigid and passively deforming leading edge". *Journal of Fluids and Structures*, 2018, 82, 329-342.

Conference Presentations:

FF Siala, MW Prier and JA Liburdy, "Force production mechanisms of a heaving and pitching foil operating in energy harvesting regime". *ASME 2018 Fluids Engineering Summer Division Meeting.*

FF Siala and JA Liburdy, "Leading edge vortex formation and detachment of a flapping foil energy harvester". *APS-DFD Meeting, 2017.*

AD Totpal, **FF Siala** and JA Liburdy, "Flow energy harvesting of an oscillating foil with rigid and passive surface flexibility". *ASME 2017 Fluids Engineering Division Summer Meeting.*

FF Siala, AD Totpal and JA Liburdy, "Optimal leading edge vortex formation of a flapping foil in energy harvesting regime". *ASME 2017 Fluids Engineering Division Summer Meeting.*

6. Impact of the Fellowship on the Fellow's Academic and Professional Development

I am very honored be a recipient of the Link Energy Fellowship. It has given me the freedom and ability to conduct research without having to worry about funding. Being a recipient of this prestigious fellowship has given me the chance to combine my passion for fluid dynamics and renewable energy to work on exciting, innovative and clean energy harvesting devices. I am certain that the Link Foundation Energy Fellowship will have a significant impact on my professional career in the future.

REFERENCES

Adrian, Ronald J & Westerweel, Jerry 2011 *Particle image velocimetry*. Cambridge University Press.

Drucker, Eliot G & Lauder, George V 1999 Locomotor forces on a swimming fish: three-dimensional vortex wake dynamics quantified using digital particle image velocimetry. *Journal of Experimental Biology* **202** (18), 2393–2412.

Ho, Steven, Nassef, Hany, Pornsinsirirak, Nick, Tai, Yu-Chong & Ho, Chih-Ming 2003 Unsteady aerodynamics and flow control for flapping wing flyers. *Progress in aerospace sciences* **39** (8), 635–681.

Kinsey, Thomas & Dumas, Guy 2008 Parametric study of an oscillating airfoil in a power-extraction regime. *AIAA journal* **46** (6), 1318–1330.

Liu, Wendi, Xiao, Qing & Cheng, Fai 2013 A bio-inspired study on tidal energy extraction with flexible flapping wings. *Bioinspiration & biomimetics* **8** (3), 036011.

McKinney, William & DeLaurier, James 1981 Wingmill: an oscillating-wing windmill. *Journal of Energy* **5** (2), 109–115.

Nakata, Toshiyuki & Liu, Hao 2012 A fluid–structure interaction model of insect flight with flexible wings. *Journal of Computational Physics* **231** (4), 1822–1847.

Nakata, T, Liu, H, Tanaka, Y, Nishihashi, N, Wang, X & Sato, A 2011 Aerodynamics of a bio-inspired flexible flapping-wing micro air vehicle. *Bioinspiration & biomimetics* **6** (4), 045002.

Noca, Flavio 1996 On the evaluation of instantaneous fluid-dynamic forces on a bluff body .

Sane, Sanjay P 2003 The aerodynamics of insect flight. *Journal of Experimental Biology* **206** (23), 4191–4208.

Siala, Firas F 2019 Experimental investigations of the unsteady aerodynamics of oscillating airfoil energy harvesters. PhD thesis, Oregon State University.

Triantafyllou, Michael S, Triantafyllou, GS & Yue, DKP 2000 Hydrodynamics of fishlike swimming. *Annual Review of Fluid Mechanics* **32** (1), 33–53.

Xiao, Qing & Zhu, Qiang 2014 A review on flow energy harvesters based on flapping foils. *Journal of Fluids and Structures* **46**, 174–191.

Young, John, Lai, Joseph CS & Platzer, Max F 2014 A review of progress and challenges in flapping foil power generation. *Progress in Aerospace Sciences* **67**, 2–28.

Zhao, Liang, Deng, Xinyan & Sane, Sanjay P 2011 Modulation of leading edge vorticity and aerodynamic forces in flexible flapping wings. *Bioinspiration & biomimetics* **6** (3), 036007.

Zhu, Qiang 2011 Optimal frequency for flow energy harvesting of a flapping foil. *Journal of Fluid Mechanics* **675**, 495–517.