An Overview of Progress in Flapping Wing Power Generation *

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Synopsis

Recently, with the increase in power generation and consumption needs of our planet, the global community has been concerned by two major issues: the severe environmental impact of burning fossil fuels and the availability of finite resources of fossil fuel for conventional power generation. These two factors are the main reason behind the search of alternative methods to harvest energy from alternate renewable sources. One such alternate method is the use of bio-inspired unsteady flapping wing power generation which has gained much interest from engineering community. At low Reynolds number, natural flyers and swimmers such as birds, insects and fish employ the unsteady vortices to generate thrust and lift which makes them one the most agile and efficient flyers and swimmers. Better understanding of the aerodynamic forces generation mechanisms associated with the flow over flapping wings can help us develop efficient micro and nano aerial vehicles (MAVs/NAVs) and with the proper phasing between different modes of wing motion, flapping wings can also be employed for the power extraction from low speed river or ocean tidal streams. It has been shown that flapping wing power generators can harness power with comparable efficiencies to that of conventional rotary wind turbines. The aerodynamics forces generation by flapping wings is a complex phenomenon and depends on many parameters like the mode of motion, phase difference between different modes, amplitude of flapping, wing shape and wing flexibility etc. Lately, there has been concerted effort to find the optimal conditions to generate maximum thrust and lift using flapping wings. In this paper, a brief overview of fundamentals of flapping wing aerodynamics and recent advancements in the research and development of the flapping wing power generators will be discussed.

Keywords— Flapping wing, bio-inspired, renewable power, tidal flows, Fluid-structure interaction.

1. Introduction

Aerodynamics of flapping wings for propulsion of micro-air vehicles and nano-air vehicles has attracted significant attention from researchers in the past two decades (Young et al. 2009, Young and Lai 2007, Taylor et al. 2003, Rozhdestvensky and Ryzhov 2003, Shyy et al. 2008), inspired by the low Reynolds number aerodynamics of flyers in nature. Many studies have tried to unlock the mystery of natural flyers or simple flapping airfoils/wings that how flapping wings at low Re are capable of generating large aerodynamic forces. This phenomenon has been mainly linked to the leading edge vortices, LEVs dynamics. The main cause of LEVs formation and shedding is found to be leading-edge separation at low Re and higher angles of attack during flapping cycle.

Similar to the low Reynolds number flight of insects, flapping wing power generating systems are characterized by massive flow separation and large leading edge vortices. It is expected that the

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anticipated flapping wing power generators could also benefit from large aerodynamic forces produced due to this unsteady mechanism and achieve comparable than the existing rotary wind turbines. More recently, in the past decade, research on the use of flapping wings for power generation is also gaining momentum (Young et al. 2014, Xiao and Zhu 2014, Rostami and M. Armandei 2017, Ashraf et al. 2011), however in comparison to research and development efforts for existing conventional rotary turbines, both Horizontal Axis Wind Turbines (HWAT) and Vertical Axis Wind Turbines (VWAT) (Bhutta et al. 2012, Hansen 2015, Eriksson et al. 2008), there is much more focused research still required to materialise the large scale implementation of flapping wing technology for power generation.

In this paper, firstly the basics of flapping wing power generation are presented and later an overview of recent progress of research in this emerging technology is presented.

2. Flapping Wing Mechanism Basics

The power extraction or excitation of an airfoil or wing by an incoming air flow is a well-known problem/phenomenon to aeronautical engineering community. As shown in Figure 1, an airfoil is allowed to oscillate vertically (plunge) and in pitch. If the combined pitch and plunge oscillation happens in such a way that the phase angle φ between the pitch and the plunge motion is 90º, then the lift force and airfoil velocity are acting in the same direction, as shown in Figure 1a. In this case, work is done by the air on the airfoil throughout the oscillation cycle (work done = Force x distance). Hence, the airfoil is extracting power out of the air flow. On the contrary, as shown in Figure 1b, if the phase angle between pitching and plunging motions is equal to zero, then during parts of the cycle the aerodynamic lift opposes the motion and no net-work is done on the airfoil. In case of flow over wings of an aircraft, for certain values of the bending and torsional stiffness of the wing, type of phenomenon shown in Figure 1a can occur on airplane wings causing catastrophic damage. This aero-elastic phenomenon generally termed as aircraft wing flutter and efforts are made to avoid or minimize it during the flight of an aircraft. However, similar type of oscillations could be used for extracting power from any flows.

This flutter phenomenon has been vigorously investigated by aeronautical engineers due mainly to the potential catastrophic damage that could be caused to an aircraft with a fluttering wing. "A fluttering wing acts as an air engine or mechanism whereby energy is absorbed from the air-stream and imparted on the wing itself" (Duncan and Delaurier 1981). Duncan's "flutter engine" might be the first flapping wing power extraction device although it was built for explaining the flutter phenomenon.

The equations for an airfoil undergoing sinusoidal plunging $y(t)$ and pitching $\theta(t)$ motions, as shown in Figure 2 are given as follows:

$$y(t)/c = h\sin(\omega t)$$

$$\theta(t) = \theta_o \sin(\omega t + \varphi)$$

where, h_o is the amplitude of motion, $\omega = 2\pi f$ is the radial frequency of motion with f as frequency of motion and ϕ is the phase difference between the pitching and plunging motions. An important flapping parameter is the reduced frequency, k:

$$k = \omega c / U_\infty$$

Further, the maximum effective angle of attack α_{max} reached in one cycle is approximated by the modulus of its quarter-period value:

$$\alpha_{max} \approx \left|\alpha_{T/4}\right| = \left|\tan^{-1}\left(\frac{\omega h}{U_\infty}\right) - \theta_o\right|$$

The effect of airfoil motion on the flow regimes is identified by a feathering parameter χ (Anderson et al., 1998), which is defined as:

$$\chi = \frac{\theta_o}{\tan^{-1}(\omega h / U_\infty)}$$

Flapping wings operate in three different regimes depending on the motion imposed on the wing and the upstream flow conditions, namely power extraction, feathering, and propulsion as described in detail in Kinsey and Dumas (Kinsey and Dumas, 2008). In the power extraction regime ($\alpha_{T/4} < 0$ and $\chi > 1$), the resultant aerodynamic force on an airfoil has a vertical component which is in the same direction as the vertical displacement; therefore, the flow performs positive work and power is extracted

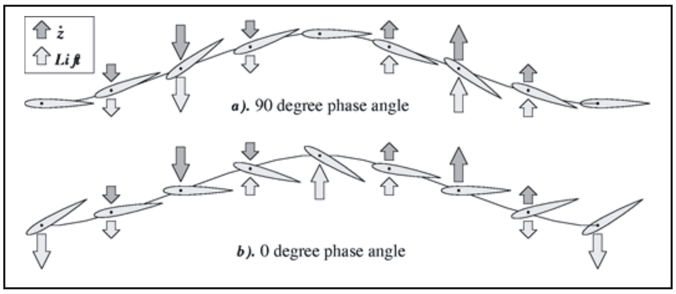

Figure 1: Bending-torsion airfoil flutter

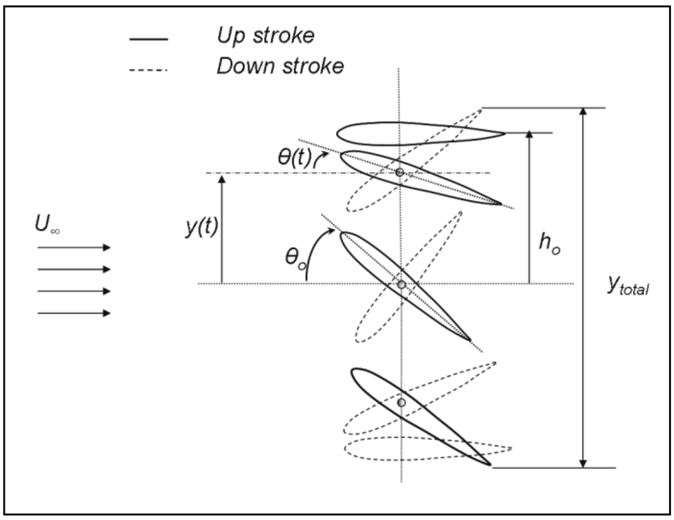

Figure 2: Airfoil undergoing combined plunging and pitching motions

from the flow because no negative work is involved with respect to the horizontal component. On the other hand, in the propulsion regime ($\alpha_{T/4} > 0$ and $\chi < 1$), an airfoil works on the fluid through the vertical component of the resultant force opposing its vertical displacement which results in a net propulsive force in the horizontal direction. Finally, the feathering limit ($\alpha_{T/4} = 0$ and $\chi = 1$) refers to a special case of a flapping airfoil flow regime in which neither thrust is produced nor power is extracted.

The mean power extracted over one cycle and computed in non-dimensional form is given by C_P which comprises the plunging, C_{Py} and pitching, $C_{P\theta}$ components:

$$C_P = \frac{P_o}{0.5\rho U_\infty^3 c}$$

$$C_{Pmean} = \frac{1}{T}\int_t^{t+T} [C_L(t)\frac{\dot{y}(t)}{U_\infty} + C_M(t)\frac{\dot{\theta}(t)c}{U_\infty}]dt$$

Further, the power extraction efficiency, η, is defined by the ratio of the power extracted, P_o, to the available power, $P_a = 0.5\,\rho U_\infty^3 y_{tot}$, where, y_{tot} is the maximum vertical distance swept by any portion of the airfoil chord, including both plunging and pitching motions, and is typically greater than $2h$. Therefore the power extraction efficiency is estimated by:

$$\eta \equiv \frac{P_o}{P_a} = C_{Pmean}\,\frac{c}{y_{tot}}$$

3. Flapping Wing Power Generators

To date, the research and development efforts on flapping wing type energy generators may be categorised into three types, based on the activation modes. These three types of flapping wing power generators are schematically shown in Figure 3. In a simplified ideal form, it is convenient to formulate the problem numerically and useful insights into the effect of different kinematic and flow parameters on the power generation efficiency of these generators could be extracted. In case of prescribed pitching and plunging motion, fixed frequency and amplitude of motion is assumed (in the power extraction regime) and analysis of flow features and power output is conducted. Much of the analysis of flapping wing turbines has been carried out with this assumption (Ashraf et al. 2011, Zhu 2011, Kinsey and Dumas 2008). This type of analysis does not involve fluid-structure interaction simulations and the power required to drive such a motion is measured. For kinematics, where time-averaged input power is negative, it is assumed that the system is extracting positive net power. In semi-flow driven motion case, the sinusoidal pitch motion is activated via a motor and the foil is allowed to move in plunge direction in response to the oscillatory forces caused by the pitching motion (Zhu et al. 2009, Zhu and Peng 2009). The power is then extracted from the plunge motion by attaching a viscous damper to model the load. The net positive power extracted is equal to the plunge minus the power required to drive the pitch motor.

In case of fully-flow drive motion, both pitch and plunge motion are generated by the fluid forces and only the oscillating motion is controlled either with a linkage mechanism or with linear or rotational springs to limit the motion amplitudes (Young et al. 2013, Young et al. 2010, Kinsey et al. 2011). Again the power output is measured by modelling a viscous damper on the plunge motion. Fluid-structure interaction analysis is required to model both semi- and fully-flow driven systems. Examples of two small-scale flapping wing power generators, built and tested by Platzer and his associates (Davids, 1999, Jones et al. 1999, Platzer et al. 2009) utilising prescribed motion and fully-flow driven motion are shown in Figures 4 and 5, respectively. First hydropower generator was tested in a water tunnel at flow speeds up to 3 ft/sec and it showed satisfactory performance. The advantage of fully flow driven flapping wing power generator is that it does not require any elaborate mechanism to maintain the wing's pitch-plunge motion at the proper phase angle between the pitch and plunge motions. In the following sections, we present few of the studies related to each activation mode.

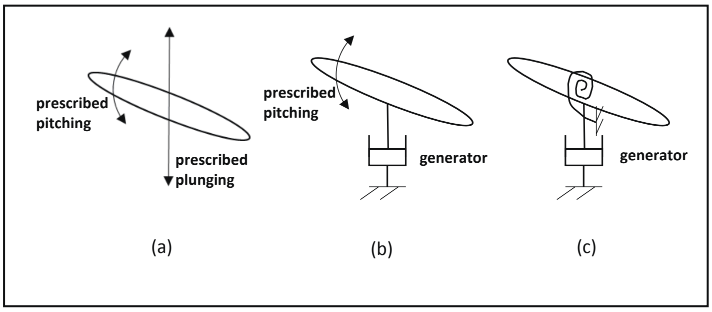

Figure 3: Schematics of flapping wing power generation systems (a) prescribed pitching and plunging motion (b) semi-flow driven motion and (c) fully flow driven motion

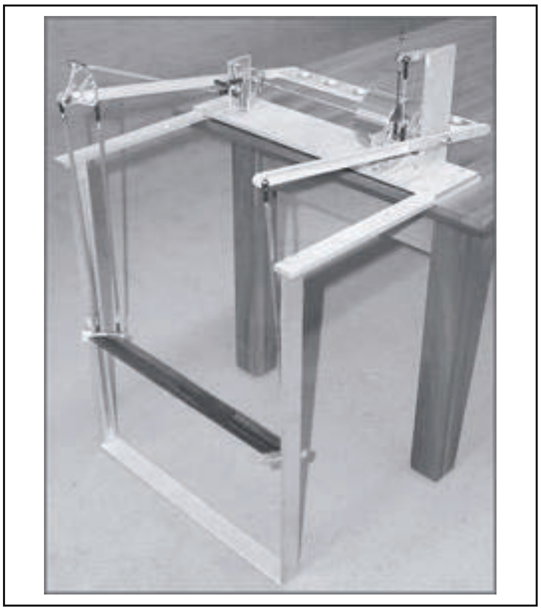

Figure 4: Single hydrofoil power generator (Davids 1999)

Figure 5: Fully flow driven flapping wing power generator (Platzer et al. 2009)

3.1 Prescribed pitching and plunging motion

Kinsey and Dumas (Kinsey and Dumas 2008) numerically studied the power generation capability of a NACA0015 foil using a viscous Navier Stokes flow solver. The flow was assumed to laminar with a Reynolds number, $Re = 1100$. The main aim of the study was to determine the maximum power extraction efficiency for the range of flapping frequency and pitch amplitude considered, whereas other parameters such as plunge amplitude, pivot location and type of motion were kept fixed. For the range of parameters considered, they found optimal reduced frequency range to be $k = 0.82 – 1.07$ and high pitch amplitude of $\theta_o > 75^o$. They reported maximum efficiency of 34%, for these optimal parameters and shown that the flow was dominated by the formation and evolution of leading edge vortices (LEVs).

Zhu (Zhu 2011) considered a single Joukowsky foil having maximum thickness of 15% with fully prescribed motion. He performed Navier Stokes simulations and also used Orr-Somerfield equation for the stability analysis of the wake. He found that the power is maximized when the frequency of the applied motion coincides with the most unstable frequency in the wake. This turn out to be similar to what Kinsey and Dumas had found. This foil-wake resonance was also found to be associated with the LEV shedding. He also reported that near the optimal performance parameters, the power required to drive the pitching motion was close to zero, suggesting the feasibility of fully flow drive systems.

Ashraf et al. (Ashraf et al. 2009) considered NACA0012 airfoil undergoing fully prescribed plunging and pitching motion at $Re = 20000$. They reported the maximum power generation efficiency of 33.5% for $k = 1.02$ and $\theta_o = 80^o$.

3.2. Semi-flow driven motion

Zhu et al. (Zhu et al. 2009) considered the semi-flow driven flapping wing power generator with prescribed pitch motion imposed. They studied the small amplitude of motion using inviscid flow solver, not accounting for flow separation and LEV formation. This study showed how the power would be extracted from flapping wing generator as this was not addressed with the fully prescribed systems. The damper, simulating a generator, was was used to model the load. They reported an efficieny of 25% for pivot point location of 0.5.

Zhu and Peng (Zhu and Peng 2009) extended this study with the viscous flow solver to capture LEV formation and shedding. They reported that positive energy extraction occurs only over a narrow range of pitching frequencies, $k = 0.8 – 1.4$. They also found that LEV dynamics are cruicial for the power output.

Shimizu et al. (Shimizu et al. 2008) performed both potential flow and Navier-Stokes simulations for a system similar to that of Zhu et al. They demonstrated that for low tip speed ratios (ratio of maximum foil velocity to free stream velocity), flapping wing power extraction performance (efficiency 35%) is better compared to 28% for the best rotary performance in low tip speed ratio regime.

3.3. Fully-flow driven motion

In fully-flow driven motion of the flapping wing power generation system, fluid-structure interaction determines the frequency of both plunging and pitching modes. Aerodynamic forces generated by the flow on the foil cause foil motion, and this change modifies the flow causing changes in force generation. Kinsey et al. (Kinsey et al. 2011) tested a fully flow driven turbine mounted underneath a boat. The turbine consisted of a two foils in tandem, using a four-link mechanism to link the pitch motion to plunge motion of each foil. The turbine was connected to an electric generator via a rotating shaft. For single foil, power generation efficiency of 30% was demonstrated for the tandem system around 40% efficiency was reported, comparable to the best performance that could be achieved with modern rotor blades turbines.

Peng and Zhu (Peng and Zhu 2009) performed analysis of fully-flow driven power genrator. They used linear and rotational springs to control the plunge and pitch amplitudes. They reported maximum power genration efficiency of 20% and found that flow driven system is highly sensitive to the position of the pivot point on the foil and the stiffness of the springs.

Young et al. (Young et al. 2010, Young et al. 2013) performed analysis of fully-flow driven power genrator. They used a one-degree-of-freedom kinematic system to link the pitch motion with the plunge motion. They conducted Navier-Stokes simulations for different pivot point location, foil and flywheel masses, pitch amplitudes and damper strength. They reported maximum power genration efficiency of 30% in the range of parameters considered.

While all results to date report critical role of LEV formation and shedding in flapping wing power generation, however, how it can be influenced by the activation mechanism is still not known. This can be achieved via detailed understanding of the physics of fluid-structure interaction.

3.4. Large scale developments

Research and development efforts in the area of flapping wing power generation has stirred the interest of industries to develop proptypes of this novel concept. The pioneer among these is the Stingray Tidal Stream Converter developed by the Engineering Business Limited and Pulse Tidal Limited (The Engineering Business Ltd. 2002, 2003, 2005, Pulse Tidal Ltd. 2019) . The equipment harnesses the tidal flow via the flapping motion of the fin which is attached to a compensator arm. As a pilot scheme, tests were conducted for an installed rating of 150 KW. However, the efficiency of this model was quite low around 11% and due to profitability concerns the project was put on hold in 2005.

Another flapping wing power generator inspired by the Tuna and Shark tail fins called bioSTREAM is being developed by the Biopower systems company (BioPower Systems 2019). A schematic of the concept is shown in Figure 6. The aim is to produce utility scale production from tidal current flows. The concept of bioSTREAM is based on the semi-flow driven flapping wing power generation mechanism. The pitching angle of the wing is imposed and the resulting plunge motion of the fin drives a specially design gearbox that converts flapping motion into a rotational one and drives the conventional dynamo. The efficiency of the model has not been reported, however a 250 kW is under development.

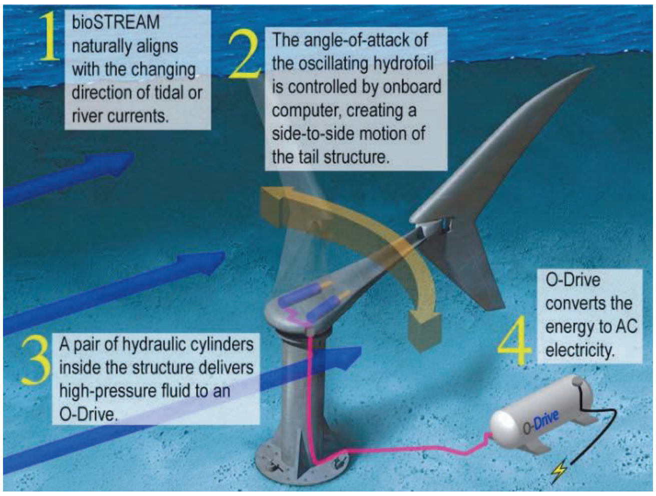

Figure 6: Fully flow driven flapping wing power generator (BioPower Systems 2019).

4. Conclusion

There have been several encouraging results of flapping wing power generators reported which makes these novel type of generators an attractive alternative to conventional rotary wind and water turbines. However, which activation mode to be employed to extract optimum performance out of the system is still needs to be explored.

The most prominent feature of flapping wing aerodynamics is the role of Leading Edge Vortices (LEVs) and their interaction with the wing and Trailing Edge Vortices (TEVs). Flapping wing power generators are shown to perform even better than modern rotary systems in low speed flows, these could be installed on the coasts of Oman to harness the tidal flows or attached to the sailing boats to generate renewable energy.

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