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A review of progress and challenges in flapping foil power generation

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ABSTRACT

Power may be extracted from a flowing fluid in a variety of ways. Turbines using one or more oscillating foils are under increasingly active investigation, as an alternative to rotary wind turbines and river, oceanic and tidal current water turbines, although industrial development is at a very nascent stage. Such flapping foil turbines promise some key potential advantages, including lower foil velocities (and hence lower noise and wildlife impact), and more effective small-scale and shallow water operation. The role of a number of parameters is investigated, including foil kinematics (modes, frequencies, amplitudes and time histories of motion), foil and system geometry (shape, configuration and structural flexibility), and flow physics effects (Reynolds number and turbulence, shear flows and ground effect). Details of the kinematics are shown to have the single largest influence on power output and efficiency (measured as the ratio of power output to that available and accessible in the fluid stream). The highest levels of power and efficiency are associated with very large foil pitch angles (upwards of 70°) and angles of attack (30–40°), such that the flow is massively separated for much of the flapping cycle, in contrast to rotary turbines which rely on attached flow over as much of the rotor disk as possible. This leads to leading edge vortices comparable in size to the foil chord, and the evolution and interaction of these vortices with the foil as it moves play a central role in determining performance. The other parameters also influence the vortex behaviour, but in general to a lesser degree. Numerous gaps in the research literature and outstanding issues are highlighted.

Contents

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1. Introduction

World population growth, the increasing demand for electricity across a wide range of human activities, and the need to reduce global greenhouse gas emissions, all underline the requirement for innovative energy generation. While fossil fuels cannot continue to meet this demand, phasing them out remains "the grandest scientific, technological, economic and social challenge of the 21st century" [1]. Replacement of coal, oil and gas in the generation of baseload electric power is unlikely to be achieved by any single technology, rather, a mix of renewable strategies will be required [2]. The power generated by the movement of the Earth's atmosphere is estimated in the hundreds of terawatts [3], which is reflected in the rapid growth of the wind power industry. Water (in the form of rivers, tidal and oceanic currents) provides much greater predictability than wind, but with significantly lower overall potential, perhaps three terrawatts [3].

Conventional rotary turbines rely on the flow remaining smoothly attached to the blades for high efficiency. In contrast, flapping foils seen in Nature have been shown to generate significantly higher instantaneous forces than can be achieved with attached flow, by allowing the flow to separate near the nose of the foil in the form of a leading edge vortex (LEV) and exploiting the attending low pressures in the vortex core. Such techniques are used by insects such as bees to create high lift from relatively small wings [4], up to four times the lift achievable by holding the wings stationary as in fixed-wing aircraft, and by marine animals to generate large propulsive and manoeuvring forces [5]. It is thus natural to consider flapping motions as an alternative to rotary methods, and particularly to explore: (i) whether power generation at low speeds and small scales can be achieved with higher efficiency than by conventional means; and (ii) whether the fluid dynamic mechanisms that work well at very low Reynolds number (e.g. $Re < 1.0 \times 10^3$ for small insects) continue to generate large instantaneous forces (and thus power) at Reynolds numbers appropriate to large-scale power generation.

Accordingly some attention has been given in recent years to novel turbines mimicking the motion of fish, shark or cetacean tails, using the motion of a flapping foil to drive a generator (e.g. [6–10]), following an approach pioneered by McKinney and DeLaurier [11]. In this concept an oscillating pitch motion (either motor-driven or passively responding to fluid forces) creates an oscillating fluid dynamic force on the foil which then plunges (heaves) in response, akin to the aerodynamic flutter phenomenon. Power is typically extracted from the plunge motion. Performance is measured as for rotary turbines, that is as the percentage of energy extracted from the fluid stream passing through the frontal area of the turbine (in this case the swept area of the foil). Limited to a theoretical maximum of 59% by the Betz criterion [12], the best rotary turbines approach 45% for single rotors at their optimum tip speed ratio (ratio of maximum foil velocity to free stream velocity), but fall sharply at low speeds [13]. Accordingly flow speeds in the order of 5–7 knots (2.5–3.2 m/s) are currently considered commercially viable for tidal stream generators [14], and 5–10 m/s for wind turbines [3,15]. Flapping foil designs promise similar performance levels while specifically benefiting from and exploiting the low speed environment, potentially expanding the commercially exploitable wind and tidal current resource base. For example, reducing the viable flow speed to 1.8 m/s could double the number of usable tidal current sites around the world [16].

This review covers recent progress in analytical and computational studies, lab-based and small scale experiments, and large scale industrial development. It reports on: (i) the effects of flapping kinematics and foil geometry, and the physics of vortex–structure interactions underlying optimal flapping performance; (ii) low and high Reynolds number considerations, and performance in real-world operational conditions such as turbulence, shear flows and time-varying flows; and (iii) challenges for future research.

2. Power generation mechanism

2.1. Flapping foil fundamentals

Extraction of power from a fluid flow using a flapping foil relies for its effectiveness on a mechanism akin to that of (and is in fact a 2D analogue of) so-called "classical" flutter in an aircraft wing. The latter requires two degrees of freedom (a combination of wing bending and torsion) interacting with a phase lag between them (e.g. [17]). The former similarly uses a plunging (heaving) motion coupled with a pitching motion of the foil about a pivot point. The plunge motion may be a pure translation as shown in Fig. 1, or a rotation of a "swing-arm" on which the foil is mounted as shown in Fig. 2.

The instantaneous aerodynamic[1] power and power coefficient, and time-averaged power coefficient are given by

$$P = L\dot{y} + M\dot{\theta} \tag{1}$$

where lift L, moment M, plunge motion y and pitch motion θ are as defined in Figs. 1 and 2.

$$C_P = \frac{P}{\frac{1}{2}\rho U_\infty^3 sc} = C_L \frac{\dot{y}}{U_\infty} + C_M \frac{\dot{\theta} c}{U_\infty} \tag{2}$$

$$\overline{C}_P = \frac{1}{T}\int_t^{t+T} C_P(t)\, dt \tag{3}$$

The efficiency of power generation is usually measured as the ratio of the time-average power output $\overline{P}$ to the power available in the flow through the frontal area swept by the foil (the so-called "Betz efficiency", in line with rotary turbine literature):

$$\eta = \frac{\overline{P}}{P_a} = \frac{\overline{P}}{\frac{1}{2}\rho U_\infty^3 sd} = \overline{C}_P \frac{c}{d} \tag{4}$$

where d is the largest total distance swept by any portion of the foil (usually the trailing edge) as shown in Fig. 3. There are a number of other definitions of efficiency in use (see discussion in Section 2.3), but all values quoted in this work have been converted to comply with Eq. (4).

These kinematics can either extract net power from the flow ("power generation mode"), or require power to be supplied ("propulsion mode"), depending on the relative magnitude of and phase between pitch and plunge motions. This is shown in

[1] The term "aerodynamic" should here be understood to be entirely equivalent to "hydrodynamic", for flows in water.