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On the aerodynamic performance of crosswind kite power systems

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ABSTRACT

This paper generalizes the classical actuator disc theory to the application of crosswind kite power systems. Here, for simplicity, it is assumed that the kite sweeps an annulus in the air, perpendicular to the wind direction (i.e. straight downwind configuration with the tether parallel to the wind). It is further assumed that the wind is uniform in space and steady in time. Expressions for the potential power output are obtained, where the effect of the kite on slowing down the wind (i.e. the induction factor) is taken into account. It is shown that neglecting the induction factor for a crosswind kite system, even when the factor is small (i.e. a few percentage points), may result in consequential overestimation of the amount of power output. Computational fluid dynamics (CFD) results for small- and large-scale kite systems are presented to corroborate the theory. It is shown that the theoretical model is fairly accurate in predicting the induction factor for such systems.

1. Introduction

Airborne Wind Energy (AWE) concerns accessing and harnessing high-altitude wind energy via either flying kites or aerostatic airborne devices such as balloons, which are usually tethered to the ground. Mean wind speed increases with altitude due to friction forces produced on the ground surface – the so-called *wind shear* phenomenon. This is what makes reaching higher altitudes appealing because wind power density is proportional to wind speed cubed (e.g. wind twice as fast (2X) has eight times (8X) the power). Winds at higher altitudes are also more consistent, which helps to increase capacity factor. Various airborne concepts and principles have been proposed and exploited to reach high altitude winds, where electricity is typically generated either by on-board turbines or by transferring mechanical power to the ground (e.g. unrolling the tether from a drum); the interested reader is referred to Fagiano and Milanese (2012); Ahrens et al. (2013); Cherubini et al. (2015); Schmehl (2018).

The principle of “crosswind kite power” was first introduced in a seminal paper by Loyd (1980). He showed that large amounts of wind power could be harvested cheaply by means of an aerodynamically efficient tethered wing (the *kite*) flying at high speed transverse to the incoming wind direction. A crosswind kite may harvest power either in *lift mode* (i.e. ground-based generation) or in *drag mode* (i.e. on-board generation). The two harvesting modes are theoretically equivalent, according to Loyd, in terms of the amount of high power generated with little material. So far in practice, neither ground-based generation nor on-board generation has been favoured, as indicated by experts involved in research and development of AWE technologies; for more details see Near Zero (2012). It is, however, their practical implementation (and unique design challenges) which distinguishes them in terms of operation, performance, and cost of energy. In fact, very active research and development is performed worldwide on this subject. For example, see Bourgault et al. (2017) for an innovative drive-train concept, involving high efficiency digital hydraulic machines coupled with hydro-pneumatic accumulators, to be used in the ground-based generation systems.

The fundamental concept of the crosswind principle is to exploit the glide ratio (i.e. the lift-to-drag ratio) of a kite to induce a much higher apparent wind speed at the kite, unlike a static kite which is only subjected to the incoming wind. This phenomenon, which sometimes referred to as *aerodynamic gearing*, in turn increases the aerodynamic driving forces of the system by a square factor of the apparent wind. Both harvesting modes take advantage of this effect to extract power, i.e. increased thrust in drag mode versus increased pulling force in lift mode. Moreover, a crosswind kite flying a closed path in the sky can extract wind power from a very large area (cf. a static kite or a conventional wind turbine). Recently, Argatov et al. (2009) proposed a “refined crosswind motion law” for lift-mode kites, including the effects of the tether drag. They also obtained a new expression for the maximal value of the mechanical power, taking into account the effects of centrifugal,

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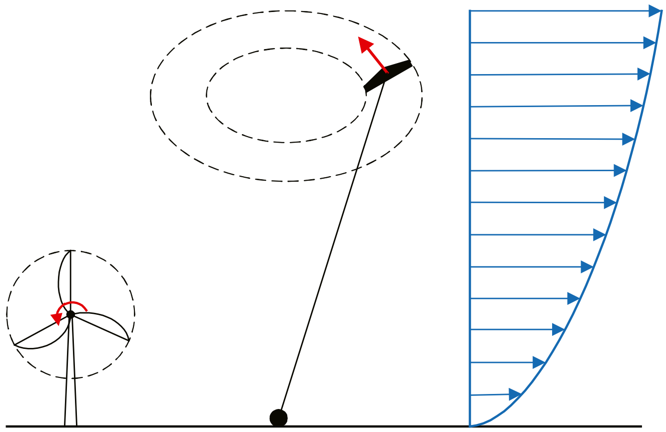

Fig. 1. Capture area of a conventional HAWT (*left*) versus an AWE crosswind kite system (*center*). The arrows to the right illustrate a typical wind velocity gradient. Almost half of the power generated by a HAWT comes from the last one-third of the blades (Bazilevs et al., 2011), but this requires a large tower structure to sustain the loads. The crosswind kite only needs a light tether, can cover a larger area and can reach more powerful winds at higher altitudes.

gravitational and frictional forces. In a subsequent paper, Argatov et al. (2011) extended the refined crosswind motion law to include effects of the kite's control and gravity.

Simplistically, a crosswind kite power system (CKPS) parallels a horizontal-axis wind turbine (HAWT), where the trajectories traced by the kite in the sky are reminiscent of the turbine blade tip (see Fig. 1). For a HAWT, approximately half of the power is generated by the last one-third of the blade (Bazilevs et al., 2011). To capture the same wind power as a HAWT, a CKPS does not require a massive hub and nacelle, a large tower structure and reinforced foundation. Instead, it requires only a single lighter blade (i.e. the kite) and lightweight tether(s) (made of ultra-high-molecular-weight polyethylene, for example). Furthermore, reaching higher-altitude winds or increasing capture area for CKPSs incurs significantly lower costs. These characteristics make CKPSs very attractive in terms of the low cost of energy produced. Despite significant advantages in employing CKPSs, and AWE systems in general, there are many technical challenges that must be addressed if these systems to become commercially viable. For example, there are many safety concerns: operating in the proximity to populated areas, or motorways or power lines, and the possibility of the occurrence of lightning strikes, just to name a few; see Lunney et al. (2017) for a detailed discussion. The reader is also referred to Bruinzeel et al. (2018) for an interesting review of ecological impact of AWE technology.

The pursuit of Crosswind Kite Power technology has only been made possible in recent years due to the advancements in electronics and control systems, light structural materials, tether technology, as well as the emergence of fully autonomous aerial vehicles. For a comprehensive review of airborne wind technologies and a list of some of the main players in the field from both academia and industry, the reader is referred to Ahrens et al. (2013); Cherubini et al. (2015).

It is well-known that there is a theoretical limit to the amount of power that can be extracted from a freestream via an energy extracting device. This limit is commonly referred to as the Betz-Joukowsky limit and may be derived from the actuator disc theory (Okulov and van Kuik, 2009). The actuator disc may be the first and simplest representation of a rotor, and, in general, of any energy extracting region in the flow. The actuator disc theory was developed in the late 1800s and early 1900s by some prominent figures in fluid mechanics, such as Rankine, Froude, Joukowsky and Betz. According to the theory (Wilson and Lissaman, 1974), a rotor is represented by a permeable disc over which the load is distributed uniformly. Using the continuity and linear axial momentum equations, expressions for the axial force acting on the disc (i.e. thrust) and power extracted from flow are found. These expressions are essential for preliminary design, performance prediction and load calculations of real turbine rotors.

Based on the actuator disc theory, the power coefficient, defined as the ratio of power extracted from flow to that available in an area equal to the disc's, is $C_p = 4a(1-a)^2$, where a is called the induction or interference factor. The induction factor is a measure of the influence of the disc on the flow, and it may be correlated to the capability of the disc to harvest power from flow. In other words, the disc extracts power by slowing down the flow, and the induction factor serves as an indicator of flow deceleration. It follows from the above expression that the maximum value of C_p is $16/27$, and it is achieved when $a = 1/3$. This means that power extraction from flow is maximized when flow is decelerated in the vicinity of the disc to $1-a = 2/3$ of the freestream velocity. This shows that power extraction does not increase monotonically with the amount of flow deceleration, but rather it reaches a limit before it starts decreasing. It is noted that for $a \geq 1/2$, the theory is no longer valid as the wake velocity, given by the theory, becomes zero or even negative, meaning that the flow direction is reversed.

As explained earlier in this section, a CKPS functions similarly to a conventional wind turbine, and it seems reasonable to use the actuator disc theory for performance prediction of the kite system. However, some researchers have expressed reservations about applying the Betz-Joukowsky limit to crosswind kite systems. For example, Loyd (1980) states that: “The criteria for the efficiency of a kite or its turbine are somewhat different from those used by Betz.” He then neglects the kite induction effect of slowing the wind, arguing that, power is maximized when induction is minimized (i.e. for a small kite area compared to the capture area) and that the actuator disc efficiency of the kite is only a few percentage points. Archer (2013) confirms that the power coefficient of AWE systems is currently unknown, but she doubts the relevance of the Betz-Joukowsky limit for AWE systems, claiming that the concept of a disc-like swept area is not applicable. Also, Costello et al. (2015) argue

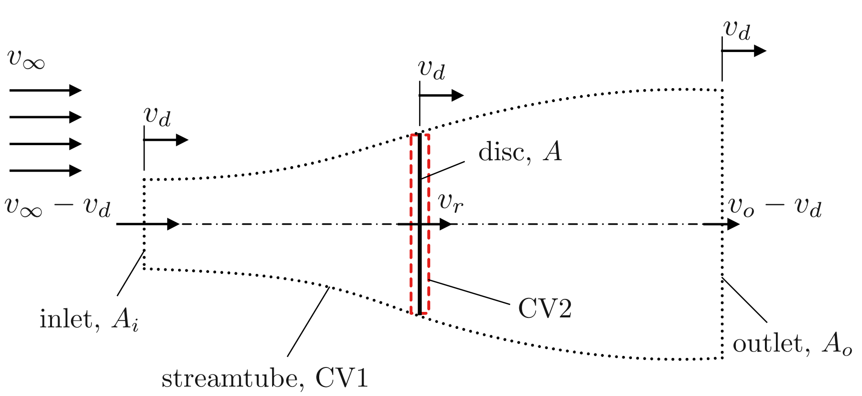

Fig. 2. A schematic showing an actuator disc (*solid line*) of area A exposed to wind flow velocity v_∞, (from the left) and moving downwind at constant speed v_d. CV1 (*dotted black line*) represents the control volume enclosing the actuator disc and also coinciding with the streamtube, while CV2 (*dashed red line*) is the control volume enclosing only the disc; both control volumes move with the disc at constant speed v_d; $(v_\infty - v_d)$ is the velocity of flow entering CV1 through inlet cross-section area A_i; v_r is the (relative) flow velocity at the actuator disc, and $(v_o - v_d)$ is the velocity of flow leaving CV1 through outlet area A_o. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)