An Updated Classification Scheme for Airborne Wind Energy Designs

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Summary
We introduce a classification scheme for an emerging field of airborne wind energy where established convention is causing a lot of confusion. The wording is chosen carefully to avoid confusion and taken from resembling behavior seen bird flight. The main category is that of either «hovering» or «bounding» mode. Furthermore energy transfer is split into four distinct methods; pulling, energy conversion, rotary shaft or reeling.

Introduction

The development of airborne wind energy [AWE] systems go a long way back, and the paper «Crosswind Kite Power» by Miles Loyd [1] stated that there were two ways to harvest energy from kites, being lift and drag mode. The terms lift and drag were already quite heavily used both in aerodynamics and in traditional windmill classification, with unrelated meaning. The heavy overloading of the terms would cause confusion in the community. Later tries to make new taxonomies for AWE, such as [5], though maybe not giving categorization enough in-depth treatment. This paper aims to replace the wording to be used by the AWE community and improve the taxonomy.

In this paper, we will present two ways to classify airborne wind energy designs that should cover known designs so far. The classification will split all known AWE designs into clearly separated categories.

What do all AWE designs have in common? They utilize the difference in flow speed at altitude versus that at the ground level. Without any such difference, there is no energy to be extracted.

An edge case would be considering something like dynamic soaring [4] to be AWE. Dynamic soaring would use a difference in wind speed at two altitudes. While dynamic soaring is extracting power from altitude, we do not consider it to be AWE. So far it seems unrelated to producing electricity or fueling transport.

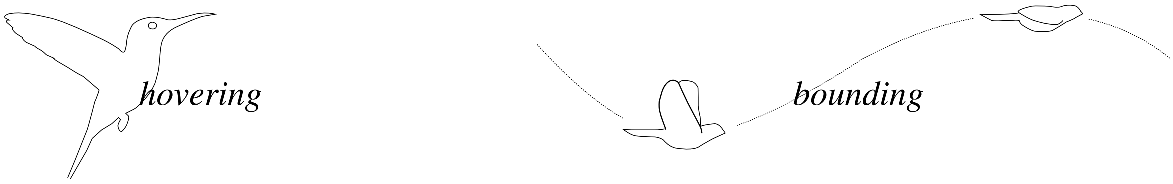
In traditional windmill designs, one generally refers to the blades of a turbine. For AWE, one generally speaks of kites. There are corner cases though where we are definitely dealing with airborne blades that are not themselves kites. One may refer to such as a tethered assembly of blades operating as a kite. To make things simpler, we will refer to any lifting surface, be it a rigid airfoil, an inflatable soft kite, gyrocopter or other design that could emerge in the future, as a turbine with blades. This also helps our AWE terminology stay aligned with traditional wind power.

Hovering or Bounding Mode?

One way of categorizing airborne wind energy systems that seems to carry a lot of importance is whether they are operating in «hovering» or «bounding» mode.

To understand the difference between hovering and bounding, look to the meaning of the words, related to bird flight. Hovering simply means flying without moving. Bounding flight is described in [2] as:

> *«These flights consist of bursts of active flapping flight alternating with passive phases, formed by glides in undulating flight and by "bounds" with folded wings in bounding flight. Mechanical energy does not flow steadily from the bird to its environment, but is stored temporarily in the bird's body in the form of kinetic or potential energy.»*



While an AWE plant producing energy in hovering mode will stay mostly stationary relative to a reference point on the ground, the bounding mode plant will let the blades drift downwind and typically use the changing tether length to extract energy. The way the bird in bounding flight will tuck its wings close to its body resembles how the blades of an AWE plant are reconfigured when reeling in the tether to try to reduce the overall drag.

Relative to M. Loyd's paper [1] bounding mode and lift mode coincide, as do hovering mode and drag mode.

When apply special consideration to AWE on a cart or a floating ship. If the AWE plant on the cart or ship is used to generate traction in somewhat the direction of travel, the plant is said to be operating in bounding mode. This holds true even if the cart or ship never de-powers the kites or blades in order to return to its origin. The physical explanation to this is that the AWE plant will be drifting downwind to a certain degree, relative to the apparent wind.

Bounding versus hovering is a classification that is rather unique to AWE relative to traditional wind power. Some drag based designs such as the the Savonius turbine do exhibit behavior that could qualify for a bounding classification; the blades move downwind when producing power, then move upwind with lesser drag. Still, we will choose limit the discussion of bounding versus hovering to airborne wind energy.

In [3] the authors conclude that hovering [drag] power systems can harvest up to $\frac{16}{27}$ of the power available in the wind while bounding systems [lift] can harvest only $\frac{4}{27}$. Note that the paper only discusses hovering and bounding systems on a stationary ground station.

Energy Transmission Method Classification

Another aspect over which we may want to classify AWE designs is their means of transferring energy. The energy is harvested at altitude and must be transferred down to ground level. We are not concerned with how the harvested energy is further used or converted once at the ground level. The four methods are described in table 1.

Pulling	The blades typically pull a tether. This is normally associated with a bounding mode design
Reeling	The design features a tether as a loop, reeling endlessly
Energy conversion	The power is typically transferred by means of electricity though a conducting tether
Rotary shaft	The power is transmitted as torque to the ground through a shaft

Table 1: Means of transmitting energy in AWE plants

Pulling transmission could be done either by elongating the tether, by moving a cart or ship or by another mechanism on the ground. Pulling transmission will inevitably happen in cycles where the tension of a single tether varies from high during production and low during return phases. The length of the cycle could coincide with the cycle frequency of the blades so that production and return phase fit into a flight pattern cycle. It could also span more flight cycles, so that the production phase includes many flight patterns cycles.

Reeling transmission would have one tether that would always be of general higher tension and one tether of lower tension. The tether would be running in an endless loop to provide continuous power delivery. If the tether was not running in a loop but rather alternating directions this may also be considered reeling transmission, if this was solved in a way that was not typical of bounding mode and pulling transmission.

Energy conversion transmission would normally mean converting mechanical aerodynamic energy from the wind into electricity that could be transferred to the ground by means of a conducting tether. One could also foresee other options where such energy was converted, as an example, to Hydrogen, then transferred to ground in a tubular tether. Another example could be where electricity was used to produce valuable data that could be sent wirelessly to the ground or elsewhere. All such schemes belong to this category.

Rotary shaft transmission would feature a shaft going from the airborne blades down to the ground station. The shaft could be a solid tube, maybe made from carbon fiber laminates. It could also be two or more tethers under tension, kept apart by aerodynamic and centrifugal forces in air, and by a rotating beam or cartwheel on the ground. Between these two extremes, shafts constituting tensile [soft] and compressive [rigid] members are also possible.

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