Review of "A small-scale and autonomous testbed for three-line delta kites applied to airborne wind energy"' by Francisco DeLosRíos-Navarrete, Jorge González-García, Iván Castro-Fernández, and Gonzalo Sánchez-Arriaga

Fernando A. Fontes, University of Porto, Portugal

Submitted to Wind Energy Science, 2024

The article presents an overview of the development of a small-scale, autonomous testbed for an airborne wind energy (AWE) system, composed of a three-line delta kite and a ground station. It provides a thorough description of the mechanical, electronic, and control systems of the testbed. The authors describe the design and construction of the testbed, which is an improvement of a pre-existing system by adding a third tether for pitch control, incorporating tensiometers and on-board load cells for precise tension measurement, and implementing a real-time controller enabling autonomous figure-eight flight trajectories.

The AWE research group at the Universidad Carlos III de Madrid, collaborating with CT Inginieros and INTA, has been working on the development of AWE systems for several years, having provided valuable contributions in theoretical modelling and control results, development of high fidelity simulators, and experimental testbeds, mainly considering systems with soft-wing (possibly with rigid frame) kites. Consequently, the article expresses the authors' mature view and expertise in the field, providing a valuable reference for the AWE community.

The control system is well explained, both regarding the mechanical actuators and the control algorithm. This last is based on a hybrid guidance strategy, combining attractor points for straight segments and continuous heading angle tracking for turns, which has been shown to be effective in achieving figure-eight paths. The authors present experimental validation of the control scheme, analyzing two flight tests and demonstrating the impact of tuning the guidance parameters on the kite's trajectory. The study includes a detailed analysis of the experimental data, including tether tensions, heading and roll angles, and the relationship between steering input and course angle. The authors also identify and model a correlation between heading rates and roll angles of the kite. The controller relies heavily on the choice of the guidance parameters, which are reported in Table 2. The impact of parameter variations in controller performance could be further investigated. It seems to me that a significant parameter that could be further analyzed is the radius of the circles centred at the attractor points, C_- and C_+. This parameter should be larger than the minimum turning radius of the kite (ocurring at the maximum roll angle), and would condition the choice of the other parameters.

Although the development and validation of a small-scale testbed – as well as the data collection it enables – are of great importance for the AWE community, a future commercially viable system would require some modifications that could be worth discussing in this article. These modifications would include not only a larger dimension, but also a reduction on the number of tethers. This is because the number of tethers can significantly hinder the power efficiency of the system. The following example shows that the use of a single tether, instead of three, can be a major advantage, more than doubling the power output of the system.

> Consider a kite system with a single tether and a similar one with three-line tether system. Let the system aerodynamic parameters be as reported in [1], with the well-studied Makani Wing 7, an 8 m wingspan, 30 kW prototype, where the aircraft drag coefficient C_{Da} is 0.06 and the tether drag coefficient C_{Dt} is 0.11 using a 160 m tether length (20 times the wingspan). The total drag coefficient for this situation is C_{D1}=0.17.
>
> Suppose that 3 tethers, instead of one are used. If the total cross section area of the tether is maintained (assuming the same total maximum load), each of the 3 tethers should have a cross section with radius $R/\sqrt(3)$ when R was the radius of the section of the previous tether. Since the drag of the tether is proportional

to the radius of its cross section, then the drag of the 3 tethers is $\sqrt(3) = 1.73$ times larger, resulting in total drag of $C_{D3} = 0.06 + 1.73 * 0.11 = 0.25$.

A well-known formula for the estimation of the power output P of a kite system establishes that the maximum power extracted is in an inverse proportion to the square of the total drag. Therefore, denoting by P_{single} and P_{three} the power output of the single tether and three-line tether systems, respectively, we have

$$\frac{P_{\text{single}}}{P_{\text{three}}} = \left(\frac{C_{D3}}{C_{D1}}\right)^2 = 2.16$$

That is, all the rest being equal, the maximum power that can be extracted using a single tether is more than the double of the power that can be extracted using a three-line tether system.

The authors could consider discussing the possibilities of using a single tether system, possibly having a single tether that splits into a variable geometry bridle, as is used in the Kitepower/ TU Delft system [ref] with a hanging control pod, or as in the University of Porto/Upwind project system [ref] with actuators for varying the bridle geometry inside the aircraft.

The authors may also want to consider discussing the possibility of using other control strategies, that could be more efficient in terms of power output than the one proposed in the article, such as the ones that use optmization-based methods and try to follow a trajectory that maximizes average power generated.

The potential for scaling up the testbed and the predicted challenges associated with such modifications are also a relevant research aspect and a discussion of some of these questions would make the article even more interesting to the AWE community.

References

[1] Damon Vander Lind. Analysis and flight test validation of high performance airborne wind turbines. In *Airborne Wind Energy*, pages 473–490. Springer, Berlin, Heidelberg, 2013.