Aero-structural Design of Composite Wings for Airborne Wind Energy Applications

Candade, Ashwin A.; Ranneberg, Maximillian; Schmehl, Roland

DOI
10.1088/1742-6596/1618/3/032016

Publication date
2020

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Citation (APA)
Candade, A. A., Ranneberg, M., & Schmehl, R. (2020). Aero-structural Design of Composite Wings for Airborne Wind Energy Applications. *Journal of Physics: Conference Series*, *1618*(3), Article 032016. https://doi.org/10.1088/1742-6596/1618/3/032016

Journal of Physics: Conference Series

Aero-structural Design of Composite Wings for Airborne Wind Energy Applications

To cite this article: Ashwin A. Candade *et al* 2020 *J. Phys.: Conf. Ser.* **1618** 032016

The Science of Making Torque from Wind (TORQUE 2020) IOP Publishing
Journal of Physics: Conference Series **1618** (2020) 032016 doi:10.1088/1742-6596/1618/3/032016

Aero-structural Design of Composite Wings for Airborne Wind Energy Applications

Ashwin A. Candade[1,2], Maximillian Ranneberg[2], and Roland Schmehl[1]

[1]Faculty of Aerospace Engineering, Delft University of Technology, Delft, Netherlands
[2]EnerKíte GmbH, Berlin, Germany.

E-mail: `a.a.candade@tudelft.nl`

Abstract. In this work we explore the initial design space for composite kites, focusing on the configuration of the bridle line system and its effect on the aeroelastic behaviour of the wing. The computational model utilises a 2D cross sectional model in conjunction with a 1D beam model (2+1D structural model) that captures the complex composite coupling effects exhibited by slender, multi-layered composite structures, while still being computationally efficient for the use at the initial iterative design stage. This structural model is coupled with a non-linear vortex lattice method (VLM) to determine the aerodynamic loading on the wing. In conjunction with the aerodynamic model, a bridle model is utilised to determine the force transfer path between the wing and the bridles connected with the tethers leading to the ground station. The structural model is coupled to the aerodynamic and bridle models in order to obtain the equilibrium aero-structural-bridle state of the kite. This computational model is utilised to perform a design space exploration to assess the effects of varied load introduction to the structure and resulting effects on the kite.

1. Introduction

Airborne wind energy (AWE) is the conversion of wind energy into electricity using tethered flying devices. Replacing towered wind turbines by lightweight tensile structure not only reduces the material effort and thus cost of energy, but also provides access to an energy potential that has not been used so far, wind at higher altitudes. In this work we consider concepts that are based on a tethered wing that is operated in cyclic flight patterns to generate power using ground-based generators [3, 7, 9]. To generate power efficiently over the entire cycle, the airborne wing is required to maximise the forces on the tether during the power phase, and minimise the force during retraction phase. From the theory of Loyd we know that the available traction power is a quadratic function of the aerodynamic lift-to-drag ratio L/D, while being linearly dependent on its lift coefficient C_L [8]. The aim to maximise the traction power leads to a design problem with conflicting requirements. More specifically, this results in a design goal to maximise the net power output per pumping cycle. This design goal results in high-lift wings which are typically subjected to a tether force an order of magnitude larger than the weight of the wing, leading to much larger wing loading compared to conventional aircraft. Over and above the high strength requirements due to large wing loading, there are restrictions on the airborne mass as well. Similar to the cut-in speed for traditional turbines, the take-off speed

Figure 1: EnerKíte technical demonstrator system comprising a mobile base station with a rotational landing and launching mast, pictured during a launching operation with a prototype wing.

for AWE systems is a crucial design parameter that depends heavily on the airborne mass, thus typically motivating high-lift, low weight wing designs for AWE systems [11].

Out of the many concepts and designs of AWE systems, the work here focuses on the tri-tether swept wing concept pioneered by EnerKíte, that utilises a hybrid carbon composite wing, composed of a carbon skeleton wrapped with a fabric covering, that is controlled from the ground. The design choices for the airborne system require it to provide typical traction forces of more than $980\,\mathrm{N/m^2}$ while maintaining a low wing mass. The higher wing loading in comparison to conventional aircraft wings is attributed to the prolonged manoeuvre loads arising from crosswind flight patterns in AWE systems. Given the influence of airborne mass on the energy output of AWE systems, a rotational mast based landing and launching system, that minimises the extra airborne mass the wing needs to carry during regular operation [12] is utilised by this system. The 30 kW mobile system EnerKíte demonstrator is depicted in Figure 1. The low mass, high strength structural requirements necessitate a rigorous modelling and optimisation process that is able to incorporate the complex load-deflection couplings witnessed in slender composite structures, right from the initial design stage.

3D solid or shell based Finite Element (FE) analysis requires upfront knowledge of internal structural geometry, laminate properties, and fibre orientations that are commonly still unknown at the initial design stage. Moreover, the high computational costs can make such analysis methods unsuitable for iterative design space exploration and optimisation. In applications where this is unavoidable, such as morphing based solutions for rigid AWE kites, 3D FE models for structural optimisation has been utilised [5]. As compared to computationally expensive shell or solid element based finite element analysis, here we utilise an alternative 2+1D methodology that models the load bearing wing-box of the wing as an equivalent 1D structure, taking into the account the unconventional 2D wing-box topology. The model also considers all coupling effects arising from the internal geometry and the composite layup [1].

Wings of AWE systems are, in addition to the aerodynamic forces, also subjected to structural forces arising from the bridle system. This system is comprised of short segments of tether, that connect the wing to the main tether that runs to the ground station. The bridle reduces the bending and torsional forces on the wing by distributing the load introduction points along the span of the wing. Experimental work has shown that the positions of the bridle attachment to the wing structure greatly influence both the static and dynamic structural response for AWE applications [13]. Furthermore, in the case of the tri-thether EnerKíte wing model, the attachment positions play an important role in the ability of steer the kite from the ground.

Previously, static analysis and optimisation was performed utilising the 2+1D structural model, complemented with an aerodynamic model to determine the aerodynamic forces and moments along the wing span, along with a bridle model to derive the resulting bridle loads [2]. In this work, a coupling step is performed with the above models to determine the static response of the wing and corresponding deformations, along with the aerodynamic and bridle load profile on the wing at this equilibrium state.

2. Objectives

The objective of the work presented here is to explore the initial design space for a composite tri-tether swept wing. Considering the fully ground-controlled concept of EnerKíte, an important aspect that needs to considered is the bridle geometry, which provides a suitable distribution of forces between the three tethers. This allows for roll and pitch control by differential force components as illustrated in Figure 2. Furthermore, a change in the attachment point of the tether influences the structural response of the wing greatly, by changing the load introduction points into structure. This effect is quite important, given the chance of unfavourable aeroelastic effects leading to divergence. Thus, the objective of this work is to perform preliminary explorations in the design space of bridle configurations in order to highlight the perils of aeroelastic effects that might not be apparent from non coupled simulations, and to find a suitable aero-structural-bridle design for the AWE system considered.

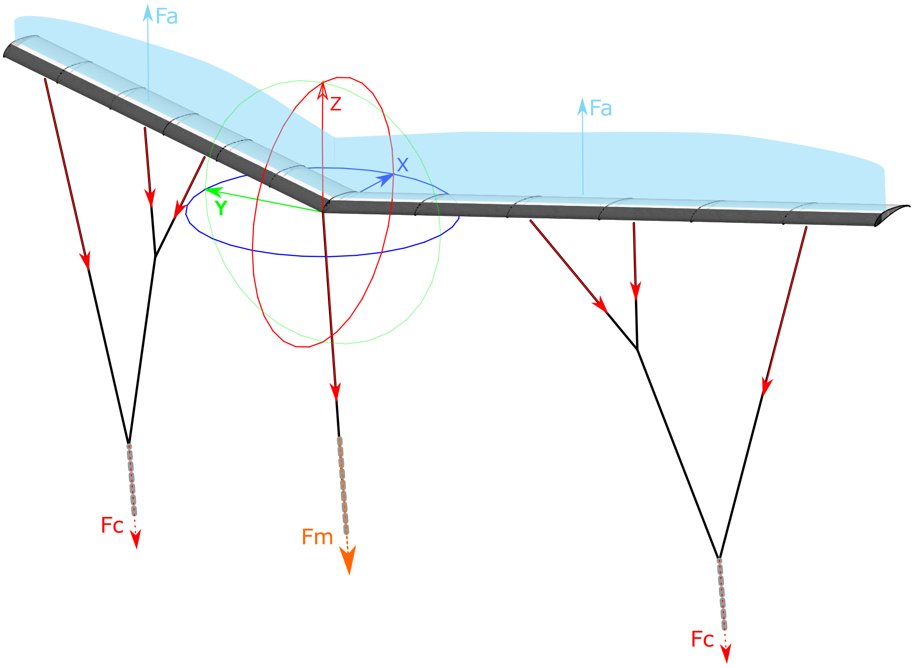


Figure 2: Typical tether and aerodynamic forces on a tri-tether swept wing AWE system. Aerodynamic force vectors F_{A} shown in blue, control line forces F_{c} illustrated in red, with main line forces F_{m} in orange. Adapted from [2].

3. Methodology

The methodology utilised here is to couple the previously described 2+1D structural model with a 1D nonlinear VLM for the aerodynamic loads, further complemented with a bridle model. These models are combined by means of a static coupling that doesn't take into account dynamic effects. The model is used to determine the equilibrium condition for the structure

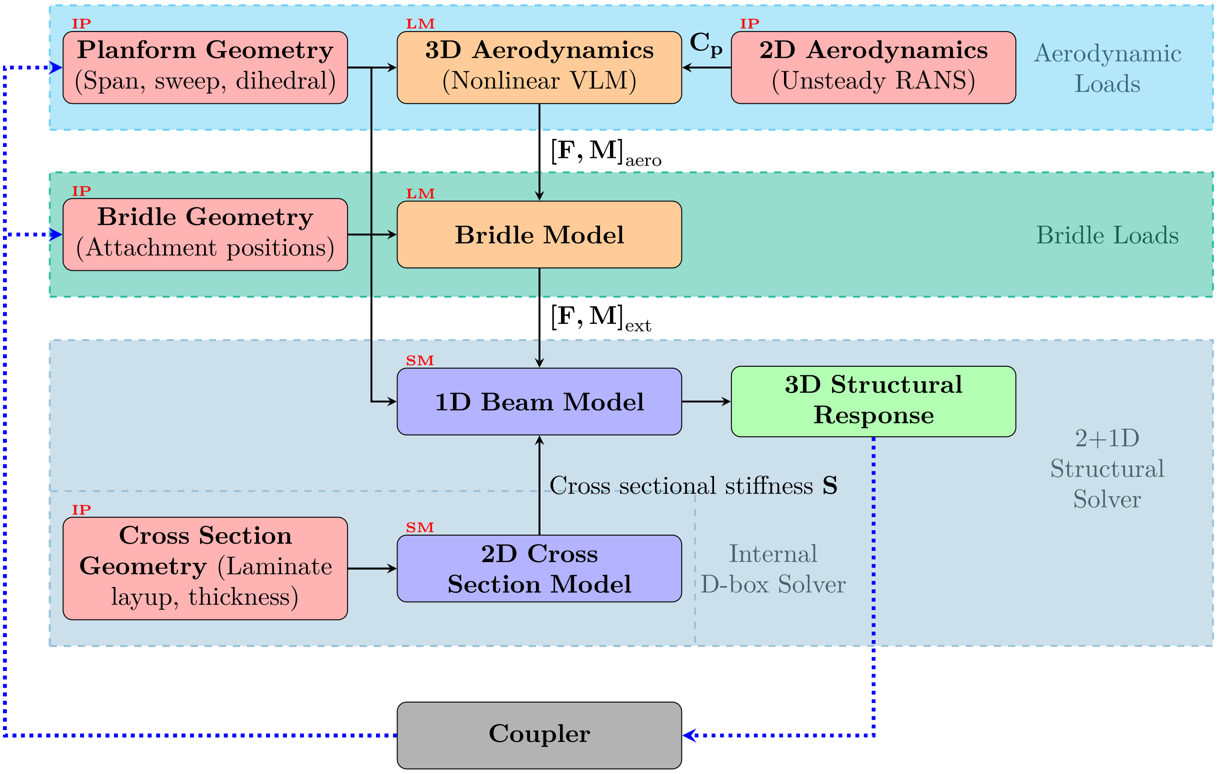


Figure 3: Computational framework overview. Inputs (**IP**) are shown in red. Models that determine loads (**LM**) are indicated in orange, and structural models (**SM**) are indicated in purple. The coupling information flow is illustrated by blue dotted lines.

for a given load case, where the load case is a function of angle of attack, wind speed, and other such parameters. This aero-structural computational model can model effects of detailed structural parameters (internal wing box geometry, composite ply layup sequence, material anisotropy effects, etc), as well as more general wing details (planform, span, sweep, dihedral, bridle geometry, etc). A schematic of the entire computational model is depicted in Figure 3. A broad overview of the implemented models are presented below in Sections 3.1, 3.2, 3.3, and 3.4. In the work here, the computational framework is utilised to analyse a tri-tethered swept wing configuration, specifically comparing effects of bridle geometry, presented in Section 4.

3.1. Structural solver

To capture the effects of internal geometry of the wing-box, laminate layup sequence and material anisotropy influences, a 2D cross sectional model is utilised. The model discretises the cross section with linear Hermitian shell elements, where the shell elemental stiffness are determined using classical laminate theory (CLT) to obtain the equivalent laminate stiffness from the ply layup. The modeller calculates a fully populated 6×6 second order Timoshenko stiffness tensor ($\mathbf{S}$) of the cross section by solving the variational asymptotic representations of the Saint Venant solutions [6].

A 1D model that captures coupling effects witnessed in slender composites based on Timoshenko theory is used. The model utilises first order shear deformation theory, and includes effects of transverse shear in the formulation, but neglects cross sectional warping effects and transverse normal strains [2]. The 2+1D structural representation is then utilised to model the structural response of the wing-box, and is illustrated in Figure 4.

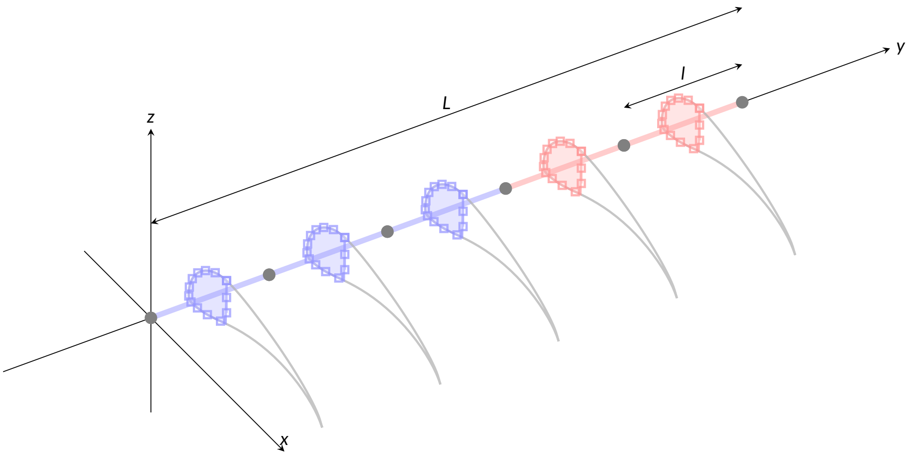


Figure 4: Structural computational model utilising a 2+1D representation of the kite structure. Adapted from [2].

In the implemented modeller, the stiffness tensor (**S**) for each unique cross section in the wing is calculated about an arbitrary reference axis — negating the requirement of the determination of the shear centre and neutral axis a priori, which is critical for any iterative design.

3.2. Aerodynamic solver

To determine the aerodynamic loads as a function of the wing planform, a single-step non-linear vortex lattice method (VLM) is utilised. Unlike traditional VLM methods that add an ad-hoc local angle of attack contribution (α-methods) in order match the local lift from the vortex and the viscous 2D airfoil lift, a so called $\mathbf{\Gamma}$ method is utilised here. In this method, the local angle of attack is not adjusted to match 2D lift slope, but instead expressed using rewritten fully nonlinear boundary conditions [10]. This methodology has since been adopted to be used in the National Renewable Energy Laboratory (NREL) AWE simulator [4].

In this stage of the analysis, the deformation of the 2D cross section is not considered, and hence the airfoil geometry doesn't deform and is considered static and thus can be precomputed in advance. The 1D tool is indifferent of methodology utilised to calculate these 2D polars. However, care should be taken as AWE wings operate typically in the near stall region where inviscid methods don't capture the reducing lift slope, and corresponding sudden increase in drag. Reynolds-averaged Navier-Stokes (RANS) or viscid-inviscid methods need to be utilised to properly model the nonlinear lift slope. In the work presented here, unsteady RANS is utilised to precompute the 2D polars for the airfoil sections.

3.3. Bridle solver

A common approach in AWE systems is to avoid a single interface point between the wing and the tether, even in the case of single tether systems. Transferring the entire magnitude of the traction force generated by the wing via a single point requires additional airborne mass for the load transfer substructure. An alternative would be to distribute the force transferred via multiple shorter segments of lines under the kite akin to wing bracing found in some traditional aircraft wing designs. An additional benefit of this approach is to reduce the root bending forces, leading to an overall lower airborne mass. However, this has to be traded against the system drag penalty the additional tether segments bring.

In the bridle subsystem, tether segments are often interconnected using pulleys, to allow for the changing attitude of the wing, with reference to the fixed ground station. For ground actuated AWE systems, the design of the bridle is crucial, as the position of the attachment points affect the controllability of the wing. This is detailed further in Section 4.1.

In order to model the bridle system, the subsystem of tethers and pulleys are modelled in the nominal equilibrium state, to determine the force magnitude and direction at each attachment point on the wing [2]. In this loading condition, the segments are under tension and thus can be modelled as straight, inextensible rigid members that extend between points. As we are interested in the static structural response, dynamic effects, pulley mass and friction are neglected, thus allowing for the pulleys to be modelled as points. Considering a single "Y" shaped bridle/pulley subsystem, under nominal loading, the tension in the top loop leads to forces in the top arms that are in equilibrium with the force in the bottom arm. The position of the pulley thus determines the direction of the forces at the attachment points (the top arms of the "Y" in this case). In more complex bridle systems, multiple pulley branches are stacked to form the bridle system. An example of such a case can be seen in Figure 5a. In such a bridle system, there is a unique load on the attachment points at the structure that can be given as a function of the aerodynamic load, the location of the attachment points, and pulley position. Depending on the location of these attachment points, they provide a means of load alleviation by reducing the root bending moment.

3.4. Aero-structural-bridle coupling strategy

In this work, we extend the static deformation capabilities of the models described above by coupling the models to determine the aero-structural-bridle equilibrium response of the system. This is achieved by coupling the deformations of the structure to aerodynamic and bridle modules as depicted by the dotted blue arrows in Figure 3. The translations and rotations determined from the structural module is used to update the location of the collocation points of the aerodynamic model. The change in local angle of attack is then determined as a function of the structural rotational deformations. An interpolation scheme is utilised to account for different mesh density of the structural and aerodynamic models. The deformed structure and corresponding new aerodynamic loads leads to a different state for the bridle subsystem, which is subsequently updated to determine the corresponding structural loading for the next iteration step. In order to aid in convergence of the entire aero-structural-bridle system, dynamic load stepping and relaxation is also implemented. This iterative cycle continues until convergence is achieved, to obtain the static equilibrium state of the aero-structural-bridle system.

4. Results and discussions

The computation model described above is utilised to analyse a representative tri-tethered swept wing configuration typical to EnerKíte. Two bridle geometries are simulated to determine the aeroelastic influence of the bridle geometry on the composite kite structure.

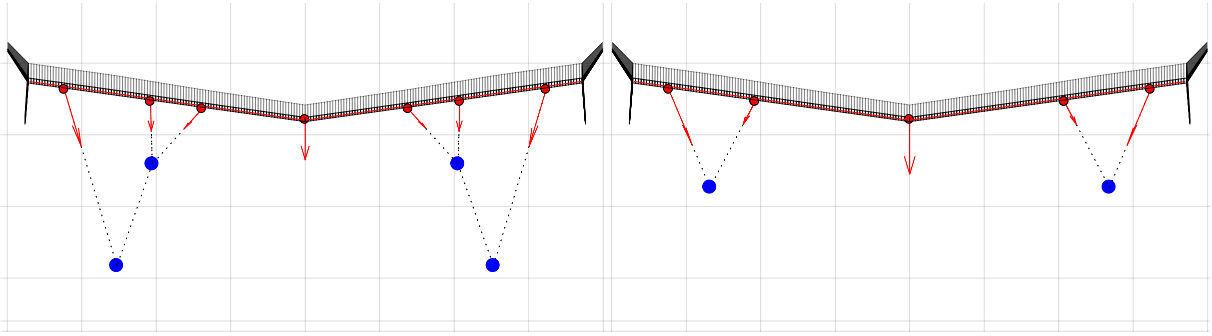
4.1. Design drivers

The choice of the bridle configuration has an impact on the load transfer path in AWE systems. Furthermore, it also plays an important role in the control of tether steered kites (both airborne and ground based steering). For configurations such as the EnerKíte tri-tether system, with all three tethers connected to the ground, pitch and roll control is achieved by differential actuation of the main line and the two steering lines. This leads to a change in the magnitude of the main (F_m) and control forces (F_c) as depicted in Figure 2. The span wise and chord wise attachment positions of the bridle, along with the aerodynamic centre of pressure leads to a force equilibrium for the system and thus an equilibrium state of the kite. Hence, in order to steer the kite, a differential force on the tethers is utilised to shift the kite into a new equilibrium attitude and position.

Similar to the pitching case, differential actuation on the two steering lines, leads to a rolling moment, and subsequently a new position of the kite. Hence, with the tri-tether system, it is possible to control both the pitch and roll of the kite, with no direct yaw control. Thus, the amount of steering force required, and stability of the kite motivates the search for different bridle configurations that could provide adequate controllability, along with multiple load introduction points into the wing, serving as a means of structural load alleviation.

Given the significance of the bridle configuration on the wing deformations determined previously [2], in this work, the structural and aerodynamic configuration of the wing system is kept constant, and only the bridle configuration is changed. Here, two bridle configurations are further analysed in order to assess their impact on the aero-structural response of the airborne system.

Depicted in Figure 5, bridle configuration “2PS” consists of two pulleys with three attachment points at the wing (Figure 5a), while bridle “1PS” utilises a single pulley with two attachment points (Figure 5b). The two configurations were chosen on the basis of static analysis with multiple bridle configurations, and choices that are detailed in Section 4.2.



(a) Double pulley configuration - “2PS” (b) Single pulley configuration - “1PS”

Figure 5: Bridle variations considered in this study. Bridle attachment points illustrated by red circles, force components in the bridle depicted in red and pulleys illustrated by blue circles. Adapted from [2].

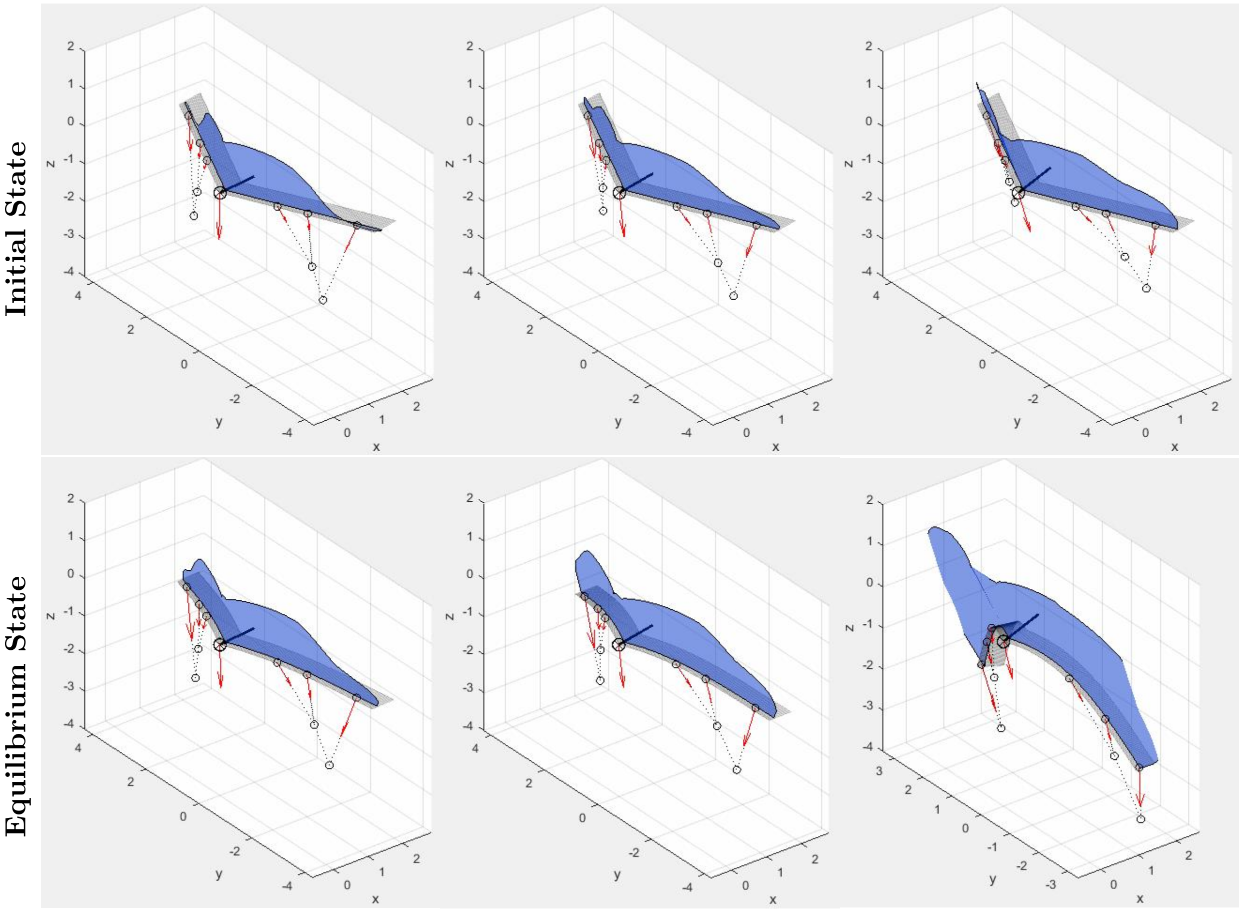
4.2. Influence of bridle configuration - aero-structural response

Aero-structural deformation results are presented in Figures 6 and 8, comparing two bridle configurations for a given wing planform and internal D-box geometry. Three increasing load cases are considered, by increasing the angle of attack ($\alpha = 5, 10$ and $20°$) while maintaining the same operational wind conditions - typical to that of a traction power generation phase for such a wing configuration.

The motivation of this design study is to determine the aeroelastic effects that arise from the variation in the load transfer from the wing-box of the kite, stemming from the two bridle configurations considered. As seen from Figures 6 and 8, the initial aerodynamic load distribution depicted in the top row is the same for both bridle cases. As the aerodynamic analysis takes into account only with the wing planform and geometry and doesn’t consider any structural deformation effects at the initial stage. Hence, this leads to an initial aerodynamic load profile that is agnostic to the bridle configurations. Thus, for the rest of the results presented here, for each of the load case considered, all other operational conditions are maintain the same with the only change being the bridle configuration between Figures 5a and 5b.

The coupled aero-structural simulations as expected leads to a different span wise aerodynamic load distribution compared to the initial non deformed wing. The deformations and rotations of the wing box leads to changes in position of the lifting surface of the wing, along with changes in the local span wise angle of attack. As seen in Figure 6a, in the case considered, this effect results in larger aerodynamic forces at the wing tips, causing a change in the load balance between the main and control lines. This has an influence on the control and stability of the kite, and after a limit leads to an unstable and non controllable kite system.

Furthermore, there are more fundamental structural implications which can be seen from the increasing load cases in Figures 6b and 6b. The increasing aerodynamic loads towards the wing tips causes an increase in the bridle forces, leading to an increased local span wise twist, leading back to an increase in the aerodynamic load. As seen in Figure 6c this leads to aeroelastic divergence, with the local angle of attack continuing to increase until structural failure. In the carbon composite wing box considered here, this effect is further aggravated by the bending-twist and tension-twist coupling modes of slender composite structures. The increasing aerodynamic loads leads to increased bending loads on the structure, which due to the bend-twist coupling leads to a rotational twist deformation of the wing-box. Moreover, when looking at Figure 5a, it can be seen that the inner most attachment points of the bridle will lead to a significant axial force component along the beam axis which contributes to the tension-twist coupling.



(a) Case 1: $\alpha = 5°$ (b) Case 2: $\alpha = 10°$ (c) Case 3: $\alpha = 20°$ (diverging)

Figure 6: Aero-structural response for bridle configuration "2PS", with increasing load cases (angle of attack α) at operational wind conditions.

Using the same load cases of $\alpha = 5, 10$ and $20°$, results for the "1PS" bridle configuration are illustrated in Figure 8. The change in the bridle configuration leads to an alternative load transfer path, given the same aerodynamic load. Similar effects of increasing aerodynamic loads towards the wing tips are witnessed. However, the magnitude of this effect is significantly lower. With less attachment points, the force component on the outermost bridle segment is higher than for the "2PS" configuration (Figure 5), which leads in larger bending forces, and thus greater deflections in the z axis. However, due to the configuration of the inner bridle attachment points, there is a lower axial force component, that leads to lower axial displacements as seen in Figure 7 for "1PS" configuration. This in turn, due the tension-twist coupling effects of the composite D-box layup, leads to a lower change in the local angle of attack $\Delta\alpha$ along the span as seen in 7. Due to this effect the "1PS" bridle configuration is also able to withstand same load case 3 (Figure 6c) in comparison to the diverging nature of bridle "2PS" (Figure 8c) for the same load condition of $\alpha = 20°$. Thus, for the same D-box geometry and the same initial aerodynamic load conditions (α and apparent wind velocity) the resulting structural response can be drastically different considering the coupled aero-structural-bridle system.

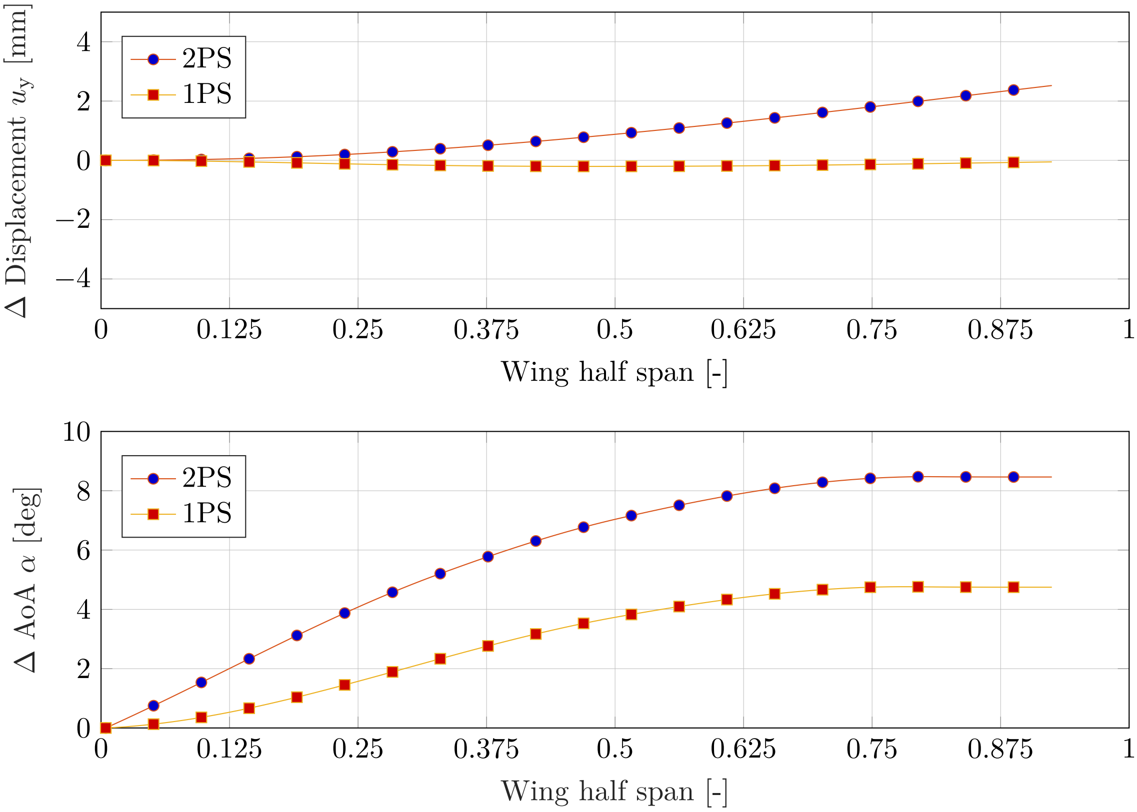
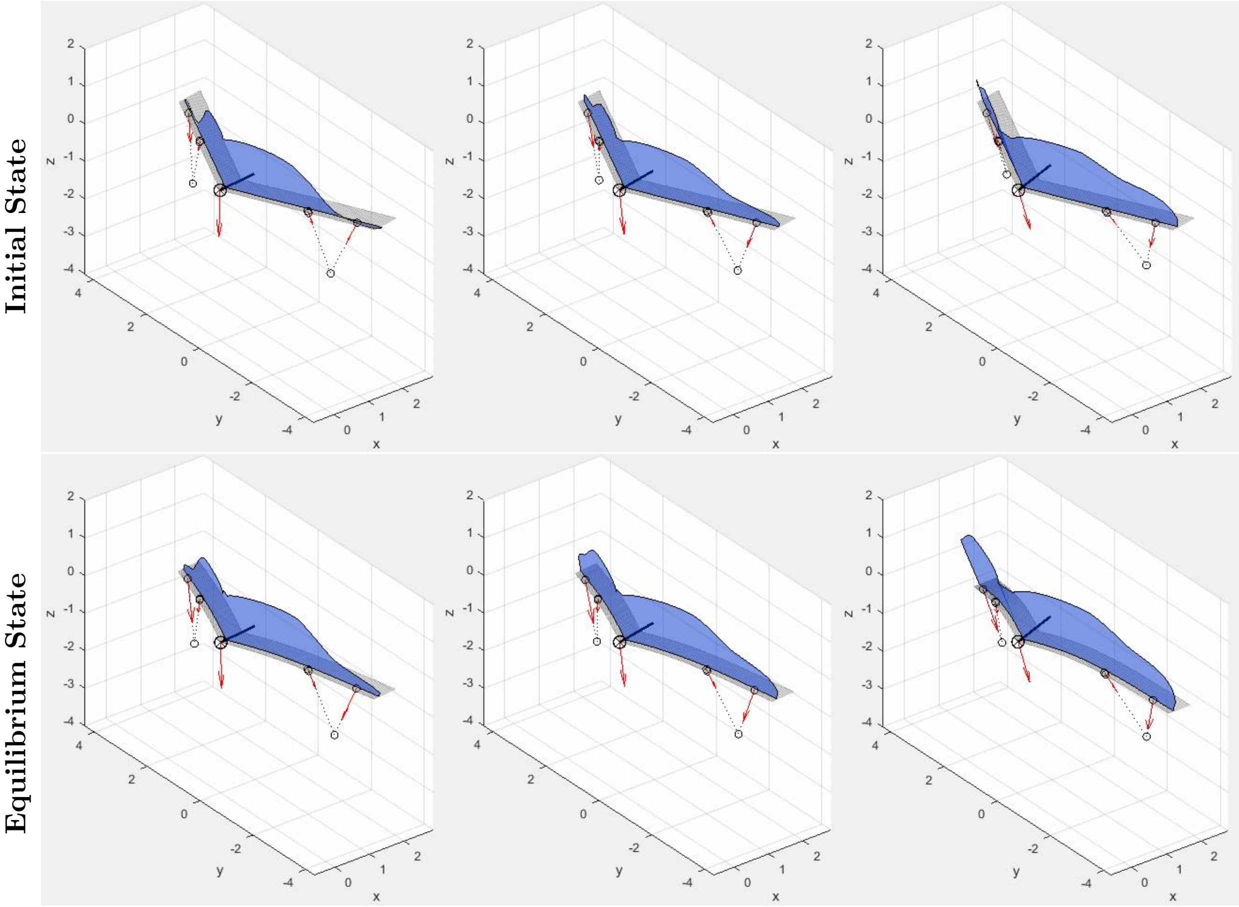


Figure 7: Change (*equilibrium* − *initial*) in axial displacements Δu_y and local Angle of Attack (AoA) $\Delta\alpha$ for "2PS" and "1PS" bridle configurations, plotted against the non dimensional wing half span for load case 2. Note that the plot axes are not equal, and are scaled.

5. Conclusions

The motivation for the work presented here on the coupled aero-structural-bridle analysis for composite kites is driven by the large wing loading, and low mass requirements on AWE systems. The utilisation of slender composite structures for their high stiffness to mass ratio leads to load-deflection coupling effects that need to be accounted for right from the initial design stage.

Comparisons between different aerodynamic load cases for two illustrative bridle configurations are made. In the current design study, the structural parameters of the D-box are



(a) Case 1: $\alpha = 5°$ (b) Case 2: $\alpha = 10°$ (c) Case 3: $\alpha = 20°$

Figure 8: Aero-structural response for bridle configuration "1PS", with increasing load cases (angle of attack α) at operational wind conditions, same as in Figure 6.

maintained the same to isolate the effects of the bridle on the aeroelastic response of the kite. The influence of the bridle geometry and attachment point locations are shown to be significant. For the case of the two bridles configurations considered here, considering increasing load cases, bridle configuration "2PS" with its increased axial force component undergoes aeroelastic divergence. This effect is alleviated by utilising a bridle configuration "1PS" that changes the axial force component, and thus the tension-twist coupling in the D-box, resulting in a stable equilibrium state for the same load condition.

The computational model developed and utilised for this is sufficiently computationally fast to be utilised in the initial design stage, allowing for a holistic design process that considers the coupled aerodynamic, bridle and structural response. Future work is currently ongoing to utilise this model to perform more design studies for bridle configurations and wing geometries, in order to further explore the design space of Airborne Wind Energy Systems.

Acknowledgments

This work is partially supported by the project AWESCO (H2020-ITN-642682) funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 642682l. Roland Schmehl has received additional financial support by the project REACH (H2020-FTIPilot-691173), funded by the European

Union's Horizon 2020 research and innovation programme under grant agreement No. 691173.

References

[1] A. Candade, M. Ranneberg, and R. Schmehl. Structural analysis and optimization of an airborne wind energy system. In M. Diehl, R. Leuthold, and R. Schmehl, editors, *The 7th International Airborne Wind Energy Conference (AWEC 2017)*, Freiburg, Germany, 2017.

[2] A. Candade, M. Ranneberg, and R. Schmehl. Structural analysis and optimization of a tethered swept wing for airborne wind energy generation. *Wind Energy*, 23(4):1006–1025, 2020.

[3] A. Cherubini, A. Papini, R. Vertechy, and M. Fontana. Airborne wind energy systems: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 51:1461–1476, November 2015.

[4] R. Damiani, F.F. Wendt, J.M Jonkman, and J. Sicard. A vortex step method for nonlinear airfoil polar data as implemented in kiteaerodyn. In *AIAA Scitech 2019 Forum*. 2019.

[5] U. Fasel, D. Keidel, G. Molinari, and P. Ermanni. Aerostructural optimization of a morphing wing for airborne wind energy applications. *Smart Materials and Structures*, 26(9):095043, 2017.

[6] E. Ferede and M. Abdalla. Cross-sectional modelling of thin-walled composite beams. In *55th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, pages 1–16, National Harbor, MD, USA, 2014.

[7] P. Jamieson. *Innovation in Wind Turbine Design.* John Wiley & Sons, Hoboken, NJ, 2 edition, 2018.

[8] M.L. Loyd. Crosswind kite power. *Journal of Energy*, 4(3):106–111, 1980.

[9] V. Nelson. *Innovative Wind Turbines: An Illustrated Guidebook.* CRC Press, Boca Raton, FL, 2019.

[10] M. Ranneberg. Direct wing design and inverse airfoil identification with the nonlinear Weissinger method. arxiv:1501.04983 [physics.flu-dyn]:1–13, 2015.

[11] M. Ranneberg, D. Brandt, A. Bormann, P. Rohde, F. Breipohl, and I. Bastigkeit. Fast power curve and yield estimation of yo-yo airborne wind energy systems. In R. Schmehl, editor, *Airborne Wind Energy – Advances in Technology Development and Research*, Green Energy and Technology, chapter 25, pages 77–95. Springer, Singapore, 2018.

[12] B. Rieck, M. Ranneberg, A. Candade, A. Bormann, and S. Skutnik. Comparison of launching & landing approaches. In M. Diehl, R. Leuthold, and R. Schmehl, editors, *The 7th International Airborne Wind Energy Conference (AWEC 2017)*, Freiburg, Germany, 2017.

[13] J. Wijnja, R. Schmehl, R. de Breuker, K. Jensen, and D. Vander Lind. Aero-elastic analysis of a large airborne wind turbine. *Journal of Guidance, Control and Dynamics*, 41(11):2374–2385, 2018.