

From a Novel Flight Mechanics Simulation Tool to a Classical Aero-Servo-Elastic Multibody Model: Bridging Dynamics and Control for the AWE Design and Future International Standards

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Keywords: AWE, flight mechanics, dynamic stability, simulation, tethered flight

Summary

Airborne Wind Energy (AWE) is an emerging field focused on harnessing wind energy using tethered flying devices such as kites and gliders. Unlike conventional wind turbines, AWE systems operate at higher altitudes where wind speeds are stronger and more consistent. To design and optimize these systems, various simulation tools of different complexity have been developed to model their aerodynamics, flight dynamics, control, tether dynamics and energy generation potential.

This paper presents a 1) novel flight mechanics simulation tool, *SILCROAD* (*Simulation Library for Craft-Object Advanced Dynamics*) developed to model and simulate the nonlinear dynamic response of a generic flying object (a *craft*) subjected to various forces (aerodynamic, gravity, thrust, buoyancy, tether, etc.) and 2) a widely used aero-servo-elastic multibody simulator *Cp-Lambda* (*Code for Performance, Loads, Aeroelasticity by Multi-Body Dynamics Analysis*), based on a finite element multibody formulation, widely used to model and simulate complex systems, such as helicopters, tiltrotors, horizontal and vertical axis wind turbines.

The purpose of these tools is to provide the research groups with in-house simulation tools that can be used in the conceptual and preliminary design, at different design phases, compliant with the future Standards IEC61400.

1. Introduction

Airborne Wind Energy (AWE) is an emerging field focused on harnessing wind energy using tethered flying devices operating at high altitudes where wind speeds are relatively stable and stronger than close to the ground. To design and optimize these complex systems, the research community has been working to develop simulation models of different complexity which can be used in the different phase of the design.

These tools can be classified according to their fidelity (low, middle, high, etc), even if this classification is more often than not very subjective and relative of one model versus another.

Simulation tools can also be classified into categories based on their focus. For instance:

- Analytical model with few (1, 3 or 6) degrees of freedom used in the very preliminary design phase to run sensitivity analysis and to study specific phenomena (i.e. interaction between wakes and wings).
- Flight dynamics models able to capture the flight mechanics phenomena (such as, stability, controllability, etc.).
- Multibody aero-servo-elastic models, to model the complex dynamic behaviour of an AWE system, including flight control strategies, tether interaction, aeroelastic phenomena (structural stability, control reversal, etc.). Also used to extract design loads under different.
- Computational Fluid Dynamics (CFD) and Finite Element Models (FEM), used in the final design phase to model accurately the aerodynamic behaviour (CFD) and the structural internal loads (FEM) once detailed drawings are available.

For decades, the POLI-Wind lab, the wind energy research group of the Department of Aerospace Science and Technology (DAER) of the Politecnico di Milano, has been actively engaged in aeroelastic simulation, control definition, and the design of conventional (land-based and off-shore) wind turbines. Inspired by and partially based on a software tool that was originally developed for rotorcraft application, the *Cp-Lambda* code has been widely used for industrial and research projects by institutes and companies for the design and certification of wind turbines and/or rotor blades. Compliant with International Standards IEC-61400 [1], the tool enables the simulation of standard-imposed load cases, extracting both maximum and fatigue loads for all wind turbine sub-components, enabling rapid and reliable machine design. Recently, discussions have emerged regarding the establishment of standards for Airborne Wind Energy Systems (AWES) ([2], [3]), which will require not only defining specific design loading conditions but also providing industry with efficient and reliable simulation tools. With this idea in mind, it is proposed to develop *Cp-Lambda* for these new future Standards in the coming years.

In parallel, in recent years, the flight mechanics research group of the DAER has been working on the development of an in-house flight dynamic simulation tool. Goal of this internal funded project is to create a completely general, fully editable and accessible tool capable of modelling an arbitrary flying system (airplane, airship, glider, helicopter, tiltrotor, etc.). This tool, named *SILCROAD* (*Simulation Library for Craft-Object Advanced Dynamics*), written in Matlab® and therefore also easy to use for students and researchers, and integrated with Simulink® and therefore with the capability to define different control strategies, allows dynamic responses, trim conditions, stability analysis in a short time, hence it can be integrated into tools for the conceptual design and control co-design.

2. Methodology

Cp-Lambda is a finite element based multibody formulation, more thoroughly described in [4]. It includes specific features useful for the modelling of complex system, such as wind turbines and rotorcraft. One of the main highlights of the code is its generality: in fact, no assumption is made a priori about the topology of the model. Rather, one can assemble the model by connecting elements from a library that includes body models (beams and rigid bodies), mechanical joints (including the lower pairs, unilateral contact conditions, and flexible joints), actuators (including prescribed displacements and rotations within joints, first order and second order actuator dynamics models, generator models, etc.). Since each element from the library can be connected to any other element, even by forming closed loops, wind turbine generators of arbitrary topology can be modelled. Thanks to this technology, any complex topology, such as multi rotor Horizontal Axis Wind Turbines (HAWT), Vertical Axis Wind Turbines (VAWT), Airborne Wind Energy systems (AWEs), Rotorcraft, Tiltrotor, etc. can be modelled and simulated (Fig. 1).

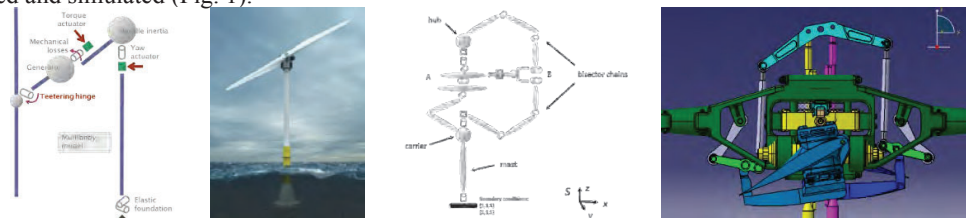


Figure 1: From left to right: *Cp-Lambda* topological schemes and CAD model of a 2-bladed offshore wind turbine and (last two images) a 2-bladed helicopter rotor with gimbal joint and flybar.

SILCROAD is developed as a library of classes, employing the built-in functionalities for object-oriented programming (OOP) in Matlab®, and connected to Simulink® for an easy control system definition.

The *SILCROAD* core is based on a *Craft* superclass, a comprehensive construct encompassing a wide range of properties and methods to define the complex dynamics of various type of aircraft. In fact, a high-fidelity nonlinear dynamic approach implementation is achieved in Matlab® through a matrix writing of the dynamic and kinematic equations of the rigid body in space [5]. Different force contributions can be included on the right-hand side of these equations based on the specific vehicle. These include aerodynamic, thrust, gravity, buoyancy forces and, now for AWE system also the tether contribution. Unlike simplified linear models, this approach can consider complex trajectories in the 3D space due to an exact and complete formulation of rotations in space. Moreover, some other non-linear phenomena, such as aerodynamic stall and inertia coupling, can be accounted for within the dynamic analysis. Last, but not least, the generalized implementation allows the simulation of a single system as well as the co-simulation of more objects in the case one has to simulate a scenario of interaction between systems, such as the case of cooperative flight or a wind farm. Possible simulations range from the capability to compute dynamic responses under different environmental conditions by imposing surface control time histories and/or

with closed-loop control systems and/or with stability augmentation systems. It is also possible to calculate trim conditions and eigenvalues. The aerodynamic model of the flying vehicle and the model for the tether cable, which are of special interest for a detailed analysis of the dynamics of a tethered glider, are implemented according to the mid-fidelity paradigm in specifically customized class (customizability and modularity are key-assets in the philosophy of programming of *SILCROAD*, seamlessly embodied in a OOP approach).

3. Results

To demonstrate *Cp-Lambda* and *SILCROAD* capabilities, some test cases have been considered choosing the Ampyx Power 2 (AP2) [6] as the reference aircraft because of the availability of data and parameters, as well as the company's willingness to share flight information. Because of limited space, only preliminary results from [7] are highlighted here to show *SILCROAD*'s ability to calculate trim conditions and dynamic responses.

Fig. 1 on the left presents a *Cp-Lambda* model. The middle one shows a *SILCROAD* longitudinal trim case, parametrized for different cone angles between 15 and 60deg. The ambient wind speed is here fixed at 22m/s, the initial (no-loaded) tether length is 400m with an equivalent spring stiffness of 1.35kN/m. The tether connection point to the aircraft is also a design parameter but is here fixed and coincident to the centre of gravity of the AWE. The third image shows a dynamic response for three different tether stiffness values in terms of body-axis speed U (longitudinal), W (vertical) and body rate q (pitch rate).

The final presentation will provide an extensive description of the tools and more examples.

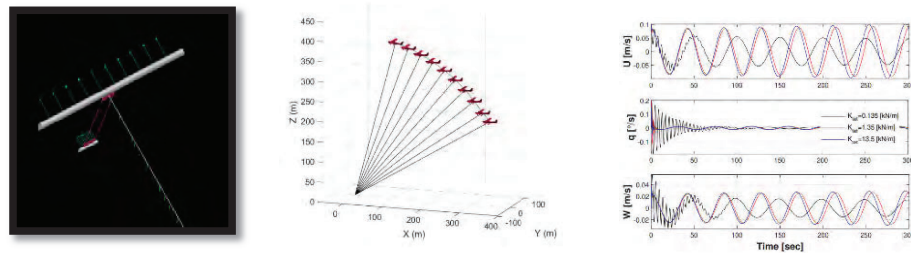


Figure 2: *Cp-Lambda* model of a rigid wing AWE system in flight (left) and (middle and right) a *SILCROAD* longitudinal trim analysis and a dynamic response.

4. Conclusions

This paper presents an ongoing research aims at developing the aero-servo-elastic multibody simulation tool *Cp-Lambda* to model an AWES in order to be compliant with the future IEC61400 standards under development for this kind of new system together with a novel flight mechanics simulation tool, *SILCROAD* (*Simulation Library for Craft-Object Advanced Dynamics*) in-house developed to model and simulate the non-linear dynamic response of a generic flying object (a craft) subjected to different type forces (aerodynamic, gravity, thrust, buoyancy, tether, etc.). The final presentation will provide an extensive description of these tools' capabilities.

Acknowledgements

This research has been partially supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).

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