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Aerodynamic Parameter Identification for an Airborne Wind Energy Pumping System ⋆

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Abstract: Airborne Wind Energy refers to systems capable of harvesting energy from the wind by flying crosswind patterns with a tethered aircraft. Tuning and validation of flight controllers for AWE systems depends on the availability of reasonable a priori models. In this paper, aerodynamic coefficients are estimated from data gathered from flight test campaign using an efficient multiple experiments model based parameter estimation algorithm. Data fitting is performed using mathematical models based on full six degree of freedom aircraft equations of motion. Several theoretical and practical aspects as well as limitations are highlighted. Finally, both model selection and estimation results are assessed by means of R-*squared* value and confidence ellipsoids.

Keywords: Airborne Wind Energy, Model-Based Parameter Estimation

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1. INTRODUCTION

Airborne wind energy (AWE) is a novel technology emerging in the field of renewable energy systems. The idea of using tethered aircraft for wind power generation, initially motivated by Loyd (Loyd, 1980), has never been closer to a large scale realization than today. High power-to-mass ratio, capacity factors, flexibility and low installation costs with respect to the current established renewable technologies, encourage both academia and industries to invest on these systems. However, complexities arise significantly in terms of control, modeling, identification, estimation and optimization. Among the different concepts in the landscape of AWE (Diehl, 2013), one interesting case study is the so called *pumping mode* AWE system (AWES). In a *pumping mode* AWES, the airplane delivers a high tension on the tether which is anchored to a ground-based generator. During *production phase*, the tether tension is used to rotate a drum that drives an electric generator. Due to finite tether length, a *retraction phase* is needed, hence the tether is wound back by changing the flight pattern in such a way that less lifting force is produced, with significant lower energy investment than what was gained during the *production phase*. A *pumping mode* AWES is being developed by Ampyx Power (AP, 2016).

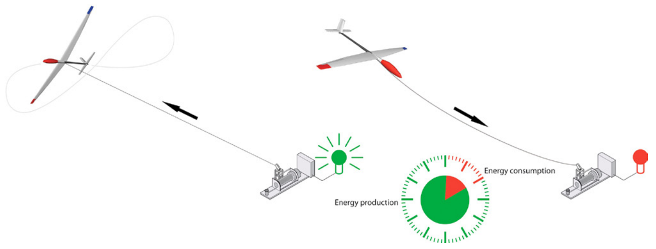

Fig. 1. Example of a pumping cycle with a *production* and *retraction phase*

The airborne component is referred to as a *PowerPlane*. An artist's rendering of the two main phases of a *pumping mode* AWES is shown in Fig. 1. The *PowerPlane*, is a high lift aircraft designed for extremely challenging operational environment including high tension from the tether and high accelerations that arise during the pattern. A concept design of the *PowerPlane* 3^{rd} generation (AP3) is shown in Fig. 2. System simulators require adequate models of the entire system, including the *PowerPlane*. Existing analysis tools such as Computational Fluid Dynamics (CFD) (Versteeg and Malalasekera, 2007) or lifting line (Anderson Jr, 2010) are able to provide initial estimates of parameters, but in most cases the full dynamic effects on the real system have to be determined through flight testing. In this case, the main issue is to describe mathematically the aerodynamic forces and moments as a function of

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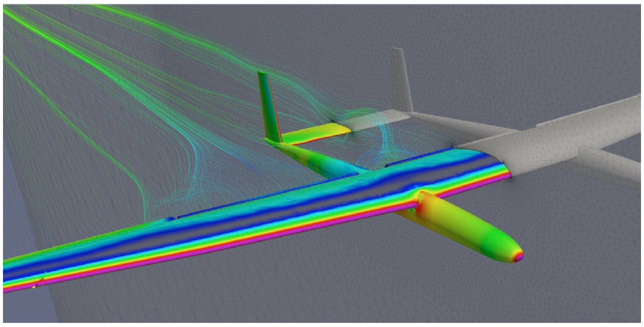

Fig. 2. CFD analysis of 3^{rd} generation *PowerPlane*

airspeed, angle of attack, angle of side slip and body rotation rates. Usually, Taylor series expansion are used to represent the aerodynamic properties. The parameters of the expansion are known as *aerodynamic derivatives* (or simply *derivatives*) and for conventional aircraft they are mainly used for control system design and handling qualities studies. For AWES, accurate modeling also enables computation of reliable trajectories by means of optimal control problems (OCPs) (Horn et al., 2013; Licitra et al., 2016), as well as design of advanced feedback controls such as non linear model predictive control (NMPC) (Zanon et al., 2013). In the aerospace field, it is the current practice to retrieve *derivatives* by empirical data obtained from similar aircraft configurations or with tools based on CFD, augmenting and verifying them by wind tunnel tests. For standard aircraft configurations such methods for obtaining aerodynamic characteristics is generally in good agreement with experimentally obtained values. However, CFD and wind tunnel tests are expensive and time consuming, and tend to be limited to static effects. Therefore, an intensive flight test campaign must be set in order to gain additional insight about aerodynamic properties. In this paper, aerodynamic derivatives are determined by means of time domain system identification techniques using measurements coming from real flight tests.

The paper is organized as follows. In Section II, model structure is retrieved from a high fidelity aircraft model augmented with description of model assumptions as well as neglected dynamics. Section III presents an efficient formulation of multiple experiment model based parameter estimation (MBPE) algorithm. In Section IV, data fitting is computed first with simulated experiments where the block structure of the nonlinear program (NLP) is shown, observation with respect to aircraft inertia are provided and confidence ellipsoids are introduced. Finally, data fitting is computed with the real experiments where the reliability of both model and estimates are assessed respectively by the *R-squared* value and confidence ellipsoids.

2. POWERPLANE MATHEMATICAL MODEL

2.1 Model Selection

A *pumping mode* AWES can be modeled via Differential Algebraic Equations (DAEs) described both by minimal (Williams et al., 2007, 2008) and non-minimal coordinates (Gros and Diehl, 2013). By means of Lagrangian mechanics one can build the equations of motion for a six degree of freedom (DOF) tethered aircraft model. For parameter estimation purposes, let us consider the translational and rotational dynamics of a *pumping mode* AWES expressed in the body-fixed reference frame:

$$m \cdot \dot{\boldsymbol{v}}_{\boldsymbol{b}} = \boldsymbol{F_c} + \boldsymbol{F_p} + \boldsymbol{F_a} + \boldsymbol{F_g} - m\,(\boldsymbol{\omega_b} \times \boldsymbol{v_b}) \tag{1a}$$

$$\mathbf{J} \cdot \dot{\boldsymbol{\omega}}_{\boldsymbol{b}} = \boldsymbol{M_c} + \boldsymbol{M_p} + \boldsymbol{M_a} - (\boldsymbol{\omega_b} \times \mathbf{J} \cdot \boldsymbol{\omega_b}) \tag{1b}$$

where $\boldsymbol{v_b} = [u, v, w]^T$ and $\boldsymbol{\omega_b} = [p, q, r]^T$ are respectively the translational and rotational speed vector, m the aircraft mass and $\mathbf{J}$ the inertia dyadic of the aircraft. The aircraft is subject to forces $\boldsymbol{F}_{(.)}$ and moments $\boldsymbol{M}_{(.)}$ coming from the **c**able, **p**ropellers, **g**ravity and the interaction between aircraft with the air mass is denoted by $\boldsymbol{F_a} = [X, Y, Z]^T$ and $\boldsymbol{M_a} = [L, M, N]^T$. Notice that, although *pumping mode* AWES does not assume any propellers during power generation phase, they are present in the studied *PowerPlane* design for assisting launch and landing as well as performing general purpose untethered flights.

In order to identify the aerodynamic forces $\boldsymbol{F_a}$ and moments $\boldsymbol{M_a}$, one has to discard or have good models of the other contributions. Hence, the flight test campaign aimed to identification of aerodynamic models should be performed without cable such that the cable does not interfere with the overall aircraft dynamics. Additionally, propellers are switched off whenever an excitation signal occurs in order to decouple the uncertainty in thrust effects on the aerodynamic parameter estimation, simplifying (1) to

$$m \cdot \dot{\boldsymbol{v}}_{\boldsymbol{b}} = \boldsymbol{F_a} + \boldsymbol{F_g} - m\,(\boldsymbol{\omega_b} \times \boldsymbol{v_b}) \tag{2a}$$

$$\mathbf{J} \cdot \dot{\boldsymbol{\omega}}_{\boldsymbol{b}} = \boldsymbol{M_a} - (\boldsymbol{\omega_b} \times \mathbf{J} \cdot \boldsymbol{\omega_b}) \tag{2b}$$

In general, the aerodynamic forces and moments are all dependent on the time history of the aircraft state in time, which mean that if the pitch moment M depends on the pitch rate q only, then:

$$M(t) = f(q(t)), t \in (-\infty, \tau] \tag{3}$$

In theory, the function in time $q(t)$ can be replaced by the following Taylor series:

$$q(t) = q(\tau) + \sum_{i=1}^{\infty} \frac{1}{i!} \frac{\partial^i q}{\partial \tau^i} (t - \tau)^i \tag{4}$$

i.e. that the whole information regarding the parameter history q is captured, if we were able to compute all the possible derivatives. However, for subsonic flight the influence of the derivatives is bounded and can be neglected with some exception (Mulder et al., 2000). Furthermore, the aerodynamic properties can be normalized with respect to the dynamic pressure $\bar{q} = \frac{1}{2}\rho V^2$ with ρ the free-stream mass density, V the free-stream airspeed, and a characteristic area for the body

$$\boldsymbol{F_a} = \bar{q}\, S \cdot [C_X\, ,\, C_Y\, ,\, C_Z]^T \tag{5a}$$

$$\boldsymbol{M_a} = \bar{q}\, S \cdot [b\, C_l\, ,\, \bar{c}\, C_m\, ,\, b\, C_n]^T \tag{5b}$$

In (5) S, b, $\bar{c}$ are respectively reference wing area, wing span and mean aerodynamic chord while C_X, C_Y, C_Z denote the forces and C_l, C_m, C_n the moment coefficients. During the system identification flight test, excitation signals are performed only along one axis in open-loop, keeping trimmed the other dynamics. Therefore, one can decouple the full dynamics in two sets of independent dynamics, three equations for the translational motion and three for the rotational one. Still, from an optimization