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Executive Summary of the Thesis

Towards the adoption of a Vortex Step Method for the aerodynamic evaluations in fixed-wing AWESs flight simulators

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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Academic year: 2021-2022

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1. Introduction

Airborne Wind Energy (AWE) is a new renewable energy sector which aims to harvest energy from high-altitude winds through tethered flying devices. Compared to traditional wind turbines, the main advantage of Airborne Wind Energy Systems (AWES) is the high-altitude wind energy extraction with fewer materials, reducing the costs and logistic problems related to the tower.

This thesis focuses on crosswind fixed-wing rigid kites that can be divided into two categories based on the energy generation type. The major information regarding the state of the art and technologies is obtained thanks to Cherubini et. al [1]. Ground Generation Airborne Wind Energy Systems (GG-AWEs) are based on a series of 'pumping cycles'. During the production phase, the kite transforms the wind's kinetic energy into traction power that reels out the tether in the generator, harvesting power. During the retraction phase, the kite is returned, ensuring the least energy is required. Fly Generation Airborne Wind Energy Systems (FG-AWEs) produce power by exploiting onboard wind turbines and transferring it to the ground thanks to special cables. The sector is growing, and many different configurations of fixed-wing kites are being tested. This thesis focuses on introducing an engineering model for low mid-fidelity aerodynamics that can be exploited for the conceptual design of AWEs. The model can support the analysis of local aerodynamic phenomena while remaining computationally efficient and versatile.

This introduction summarises the first part of the thesis, including the first chapter of state-of-the-art and technological analysis. Hereinafter, each section represents a chapter of the thesis and reports relevant results.

2. AWEs simulation tools: a state of the art review

Chapter 2 of the thesis presents an overview of open-source software for AWEs simulation. The aim of the analysis is to understand which mathematical models are exploited, with special attention to the aerodynamic model. The simulators taken into consideration are:

1. *KiteFast*, a multi-physics engineering tool for modelling the coupled aero-servo-elastic dynamics of AWEs. The quasi-steady induction is computed from lifting lines using the Vortex Step Method (VSM). The lat-

ter is a very promising aerodynamic model. However, the computational environment is complex due to the many programs present.

2. Delft MegAWEs, a simulator that can model 3 DoF & 6 DoF kite dynamics. The optimisation framework behind it is based on a Fluid-Structure Interaction (FSI) combined with a flight dynamics simulation model. The aerodynamic module is based on a Look-Up Table (LUT) in the latest simulator version. The computational environment is interesting since it is mainly based on MATLAB & Simulink.
3. LT-GliDe, a program completely written in MATLAB that involves a linearization problem. The approach on which the code is based allows for studying the AWEs system dynamics, with the kite set to a state representative of its flight during the power generation loop ([4]). The aerodynamic model is based on the Prandtl Lifting Line theory.
4. LASKA, a simulator based 100 % on MATLAB used for the dynamic analysis of tethered flying vehicles such as kites and fixed-wing drones. It comprises four simulators based on minimal coordinate Lagrangian formulations and can be used for FG and GG systems. The aerodynamic model is based on a LUT.

The results obtained are summarized in table 1.

Table 1: Models' comparison.

Simulator name	**Aerodynamic model**	**Environment**
KiteFast	**VSM**	MATLAB/Phyton Fortran
MegAWES	LUT/FSI	MATLAB Simulink
LT-GliDe	Prandtl LLT	MATLAB
LASKA	LUT	MATLAB

The more interesting simulation environment appears to be **Delft MegAWEs**. However, the related aerodynamic module is based on the selection between a specific LUT that is not versatile and an FSI algorithm that is highly computationally demanding. This situation is shared among the other simulators, where a LUT is mostly exploited. The interesting model is the VSM presented in KiteFast. The following thesis develops a similar VSM, believing that it could be the proper low-fidelity aerodynamic method exploitable for the conceptual design of AWEs, creating an intermediate possibility between a simple LUT and more complex models like the FSI.

3. Aerodynamic model modifications

In Chapter 3 of the thesis, the VSM aerodynamic model is introduced theoretically, comparing it to the Lifting Line Theory (LLT) and the Vortex Lattice Method (VLM). Immediately after, the implementation is presented, followed by validation.

The validation follows a build-up approach from the analytic solution of a single elliptic wing up to the introduction of the horizontal tail. The VSM is compared with the extensively validated Tornado VLM; given that the latter is mostly used for conceptual design, it is computationally efficient and a potential method, then it is considered the perfect candidate for this comparison. Finally, the vertical tail is introduced, which is paramount for future dynamic simulations.

3.1. Implementation of the VSM and potentiality of the method

The VSM presented in this thesis is versatile; the horseshoe filament vortex can be made of three filaments or five filaments. Moreover, there is the possibility of modifying an input string, passing from the VSM to the LLT. The big difference resides in the control point in which the boundary condition is applied ($\frac{1}{4}c$ for the LLT and $\frac{3}{4}c$ for the VSM). While modifying the boundary condition, a new constraint equation is introduced (eq. (1)):

$$\begin{aligned} \mathbf{f} = \rho\,|\mathbf{U}_\infty \times \mathbf{\Gamma}(y)| &+ \\ -\frac{1}{2}\,\rho\,|\mathbf{U}_{rel} \times \hat{z}_{airf}|^2\, c\, C_l(\alpha, \delta_f) &= 0 \end{aligned} \tag{1}$$

The potentiality of the VSM is attributed to the possibility of introducing non-linearity thanks to the airfoil polars interpolation $C_l(\alpha, \delta_f)$. Hence, the method can consider the airfoil's non-linear effect and the presence of flaps or moving surfaces.

kite geometries exploited for the analysis The kite used for the analysis are the Zefiro kite, presented in [4], and the Delft MegAWEs kite, presented in [2].

3.2. Validation: single elliptic wing

The validation with a single elliptic wing is performed since the analytical expression for the lift and drag coefficients is achievable with the analytical LLT. In fig. 1 and fig. 2 a comparison is shown for a case in which the kite is flying with an airspeed x-component (V_x = 45 m/s), and the wind speed has a single component along z to excite the lift, ranging from -4 m/s up to -10 m/s with a -1 m/s step. Furthermore, 11 discretisation sections along the wing are present.

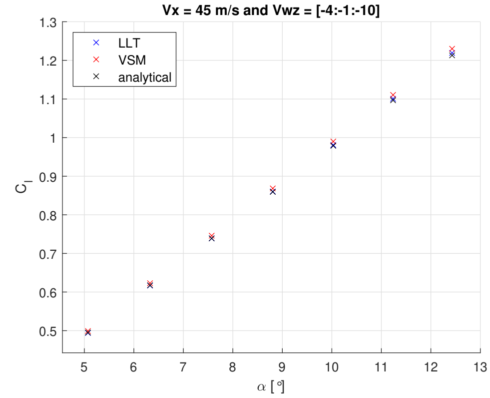

Figure 1: Lift coefficient with respect to the angle of attack variation for an elliptic wing.

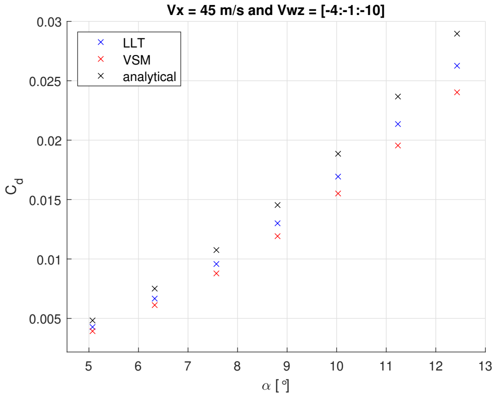

Figure 2: Drag coefficient with respect to the angle of attack variation for an elliptic wing.

The same test has been performed for a variation of the x-component of the kite airspeed, with a modification in the values of the lift and drag coefficient. Consequently, an increase in the number of discretisation sections is analysed, reducing the percentage error, especially for the drag coefficient obtained with the LLT implemented in the code, as visible in fig. 3.

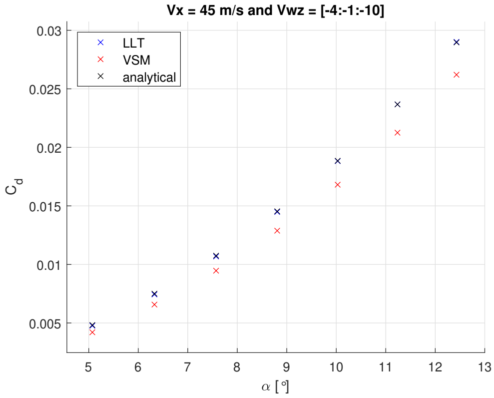

Figure 3: Elliptic wing - case with Vx = 45 m/s, variable wind speed along the z-axis and 31 aerodynamic sections along the wing.

Moreover, an increase in the aspect ratio was performed, from the initial AR = 16 up to a value of 30. The error in the drag coefficient estimation is also reduced for the VSM. Nevertheless, a discrepancy is still expected since the VSM is a different method with a different control point with respect to the LLT.

3.3. Validation: elliptic wing with dihedral and sweep angles

The second case of validation is related to the introduction of the dihedral and sweep angle on the same elliptic wing presented before. Introducing the dihedral angle is fundamental, especially for the conceptual design of AWEs. It stabilises the aircraft around the roll axis, and an AWE flies into a chaotic environment. Therefore, an aerodynamic model incorporating this angle correctly could be exploited for many analyses. The same goes for the sweep angle, paramount for flight stability analyses. A comparison between the analytic stability derivative due to sideslip, obtained from Roskam, estimated with Tornado VLM, and the VSM code, is visible in table 2.

Table 2: C_{L_β} comparison Tornado VLM - VSM - Roskam.

	Tornado VLM	VSM	Roskam
C_{L_β} $(\Gamma = -5°)$	-0.019	-0.014	-0.017
C_{L_β} $(\Gamma = -7°)$	-0.131	-0.127	-0.135
C_{L_β} $(\Gamma = -9°)$	-0.167	-0.284	-0.197

3.4. Validation: elliptic wing and horizontal tail

The horizontal tail has been introduced considering the geometric parameterisation of the Zefiro kite. A model with a horizontal tail is paramount since the latter is fundamental for stability and controllability.

Two analyses have been performed:

- Moment representation with single wing and with the addition of the horizontal tail. Used to verify the effective increase in moments when introducing the horizontal tail.
- A comparison between the downwash angle computed thanks to [3] and the same angle exploiting the induced velocities obtained from the VSM code while moving the tail far away from the wing.

The results for the downwash angle are presented in fig. 4, where a similar trend is visible but it tends to diverge while increasing the distance from the wing. This could be traced back to the analytic model. The latter is based on a single horseshoe vortex configuration, with the vortex extending from the tips of the wing to infinity. In contrast, in the VSM code, several five filaments horseshoe vortex are presented, leading to a more conservative solution.

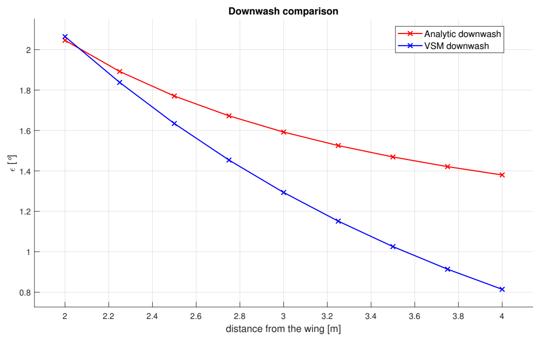

Figure 4: Comparison between analytic and VSM downwash angles for an elliptic wing with no dihedral or sweep angle.

3.5. VSM - VLM comparison

The Tornado VLM is introduced and simplified to have the same inputs as the VSM. A comparison of the two methods concerning the aerodynamic forces obtained is visible in fig. 5. The latter is also used to estimate the computational time, showing good behaviour of the VSM, with computational times similar to the VLM.

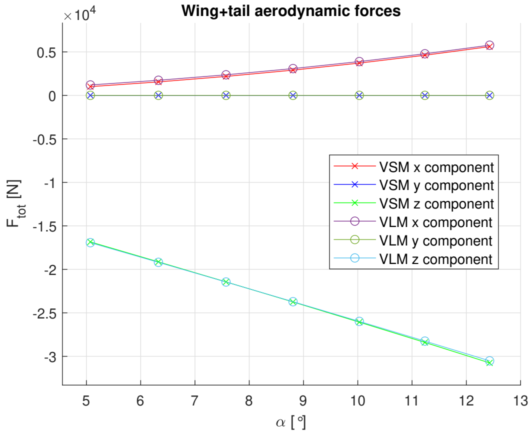

Figure 5: Wing and horizontal tail aerodynamic forces with respect to angle of attack variation for the Zefiro kite: VLM vs VSM.

3.6. Vertical tail introduction

The final step consists of the introduction of the vertical tail. The code is created so that a simple modification of its settings would translate into introducing a new surface. The tail has an exaggerated dimension on purpose to stick with the elliptic shape used for all the previous analyses.

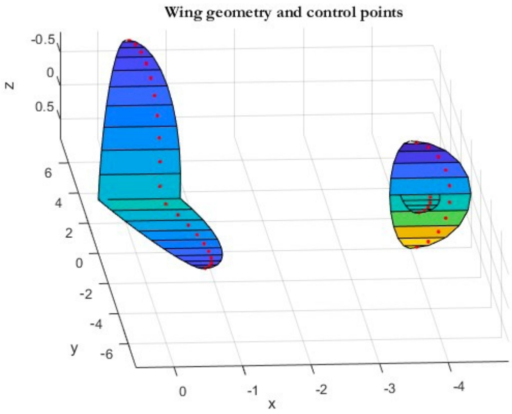

Figure 6: Wing and complete tail geometry together with the control points.

The vertical tail is paramount since the next step consists of the kite trim analysis (section 4) that requires the vertical empennage to succeed.

4. Trim of the kite and dynamic simulation

In Chapter 4 of the thesis, the generalized trim of the kite is investigated to verify if the VSM performs well and to find a suitable initial guess for a possible dynamic simulation.

Assumptions The Delft MegAWEs environment is not considered since extensive work to modify the control is required to make it compatible with the VSM. The **tether model** for the first trim analysis is simplified; thereafter, the complete tether model exploited in Delft MegAWEs is exploited for a final comparison. A constant wind field is used during the trim since accurate power prediction is not the purpose of this thesis. Finally, control surfaces must be introduced for a simplified yet effective simulation. Since they have not been physically designed yet, the idea is to account for the effect of control surface deflection through a lift coefficient (ΔC_L) introduced while interpolating the airfoil polars.

4.1. Generalized trim of the kite

Gravitational and aerodynamic forces related to the mean elevation angle of the kite are discarded. Centrifugal forces are balanced by the radial component of the tether. It is paramount to specify that a numerical problem appeared while analysing the trim, probably due to the introduction of the vertical tail and its interaction with the other surfaces or the control surfaces while interpolating the airfoil polars. Therefore, the implemented LLT is exploited to find the trim solution, being aware that once the numerical problem is solved, the same trim analysis could be launched simply by modifying an input.

Four reference systems are introduced: the body reference system ($\mathcal{RF}_B$), the ground reference system ($\mathcal{RF}_G$), the rotating reference frame ($\mathcal{RF}_R$), and the stability reference system ($\mathcal{RF}_S$).

Thanks to the selection of the initial state for the trim, $\mathcal{RF}_R$ and $\mathcal{RF}_G$ are aligned, the rotation matrix is much simpler and involves just the pitch angle. The latter is prescribed; therefore, the problem is translated into trimming the kite while maintaining a specific pitch angle and finding the six state variables that can trim it:

- U_0 is the kite airspeed in the stability reference frame;
- R_0 is the radius of gyration;
- ε_t is the tether deformation parameters;
- Three δ values, including the three lift coefficient offsets (ΔC_L) generated by the elevator, ailerons and rudder.

The physics and ruggedness of the trim condition have been analysed for a null value of the pitch angle. Regarding the actual forces and moments acting on the kite at trim, they are as expected, the lift is negative accordingly, the y-component of the forces acting on the tether is dragging the kite into the centre of the circular path, and the centrifugal force is positive, pushing the kite out of the trajectory. Several other tests for the practicality of the trim conditions have been done: variation of the pitch angle, variation of the kite's mass and modification of the tether attachment point.

4.2. Trim condition with the complete tether model

The last comparison is made between the trim condition obtained with the simplified version of the tether and the trim condition obtained with the complete tether model extracted from the Delft MegAWEs simulator. The forces are similar (table 3); hence, a more complex and difficult tether model can be introduced, and the low-fidelity aerodynamic model presented in the thesis can efficiently connect with this trim condition and with complex models.

Table 3: Tether force comparison.

[kN]	F_{Tx}	F_{Ty}	F_{Tz}
Simplified model	-1.66	-5.75	1.71
Williams model	-1.67	-6.63	1.66

5. Conclusions

This thesis analyses the possibility of exploiting an engineering model of low-fidelity aerodynamics for the conceptual design of AWEs. The introduction and implementation of the VSM can support the analysis of local aerodynamic phenomena. The potentiality of this method resides in the possibility of introducing non-linearity through airfoil polars interpolation. Firstly, an analysis of the functionality of AWEs has been performed, followed by a state-of-the-art review of the available tools for AWEs simulations. The validation of the code has shown that the VSM is versatile and computationally efficient; following a build-up approach, relevant aspects have been touched upon. The geometry is modified accordingly while varying important angles; moreover, the code can easily introduce more lifting surfaces. Compared with an extended validated code like Tornado VLM, the VSM has shown effectiveness in estimating aerodynamic forces. The kite's generalised trim has been analyzed thanks to the vertical tail's introduction. A simplified yet effective solution for introducing the control surfaces has led to a trim problem based on six state variables. The trim condition has been physically analysed, observing how the force reacts along the circular trajectory and verifying the ruggedness of the trim condition through different parameter variations. Moreover, simplified and more complex tether models have been compared, showing that the trim problem is correctly stated. The trim condition could be a suitable initial guess for future dynamic simulation.

6. Recommendations and Future developments

The most relevant *issue* to be investigated is the numerical error presented while trimming the kite exploiting the VSM. A severe analysis has restricted the investigation to two areas:

- A problem related to how the code detects the induction between surfaces, especially vertical tail - horizontal tail induction;
- A problem in how the code detects the geometric discretisation since an unexpected jump is presented while passing from one surface to the other.

The most important *future developments* are summarised herein:

- Implementation of a vortex core correction;
- Airfoil data extraction from CFD database and the possibility of introducing different airfoils on the same surface (aerodynamic twist).
- Helicoidal wake: the modelling of the aerodynamic wake of AWEs is crucial for estimating their performance and design. The VSM can model the induced velocities at the AWEs in a consistent way. In this first version of the code, a straight wake is used, but according to Trevisi et al. [5], the introduction of a vortex model for the wake, exploiting helicoidal filaments, is possible.
- Having the possibility of relying on an efficient and general aerodynamic method, a physically feasible trim condition and an oculate ODE simulation, the kite could be exploited as a **sensor** to be put in front of wind turbine farms to extract relevant wind information, in particular, **wind intensity, wind direction** and **wind shear**.

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