Optimal Control of Airborne Atmospheric Actuators with a Vortex-Ring based Wake Model

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Introduction

Airborne actuating systems can be used to influence the flow through wind farms ("airborne atmospheric actuator" - AAA) or as an energy-generating device ("airborne wind energy" - AWE)

Similar to wind turbines, the downstream wake heavily influences performance and must be included in flight trajectory optimization.

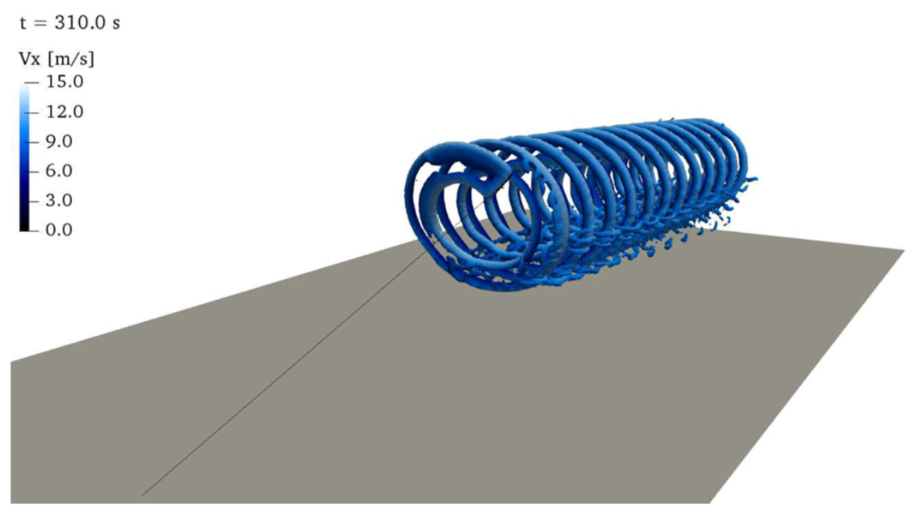

Figure 1: Haas et al, Large-eddy simulation of airborne wind energy farms, Wind Energ. Sci., 7, 1093–1135, 2022

Low-fidelity wake models based on momentum balance are not suited for the airborne setting. High-fidelity models (Fig. 1) are numerically intractable.

GOAL: discretize vortex structure with geometric shapes (here: vortex rings), to obtain tractable mid-fidelity wake model.

The continuous **wake structure** of **airborne actuators** can be discretized by a finite number of **vortex rings** to obtain a mid-fidelity tractable **optimization model**

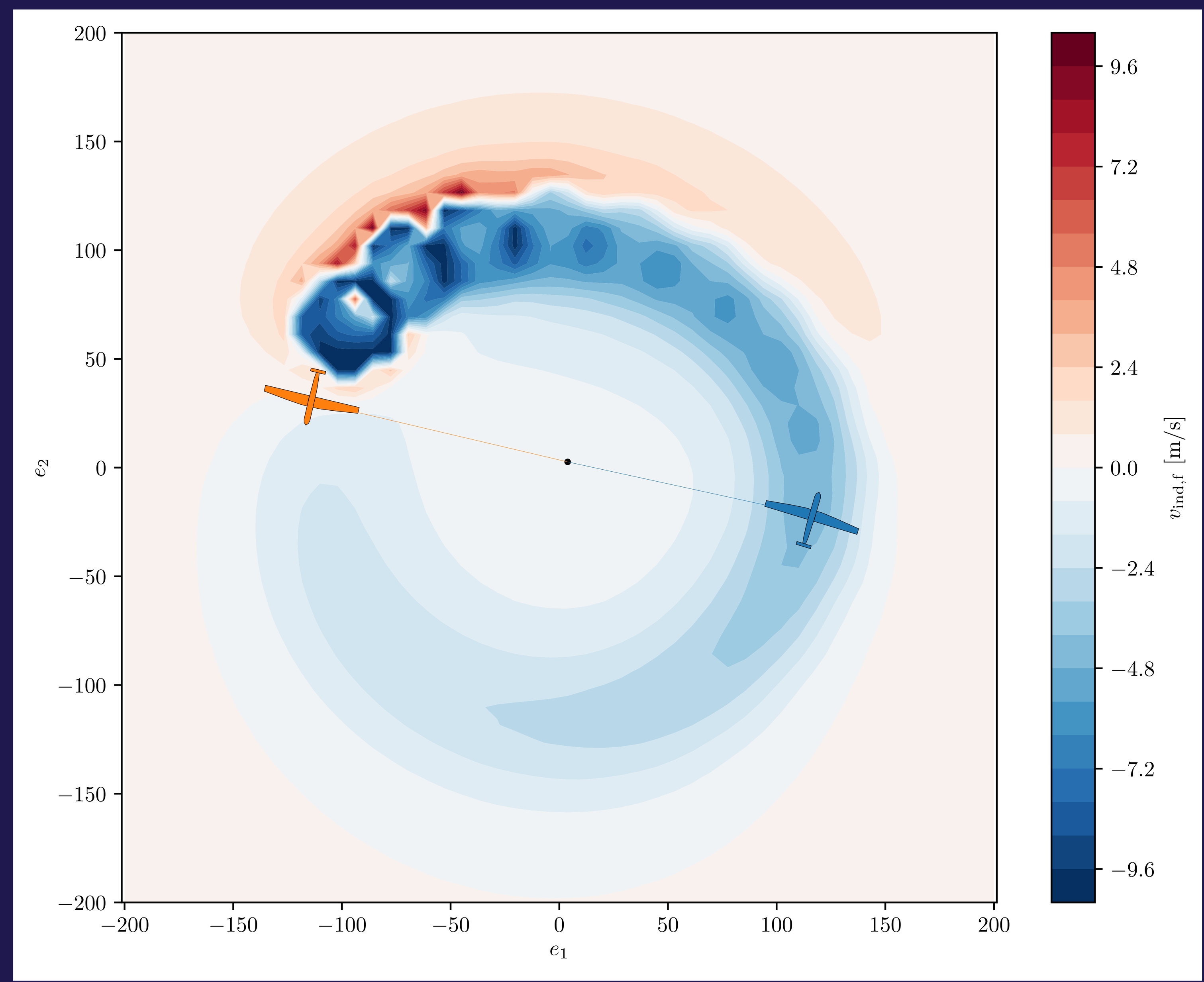

Figure 2: Dual-wing AAA optimal flight trajectory for v_w = 12 m/s, with 2x10-ring vortex ring model and a wake memory of 3 rotations. The computation time of 2090 s is two orders of magnitude higher compared to the problem w/o wake model.

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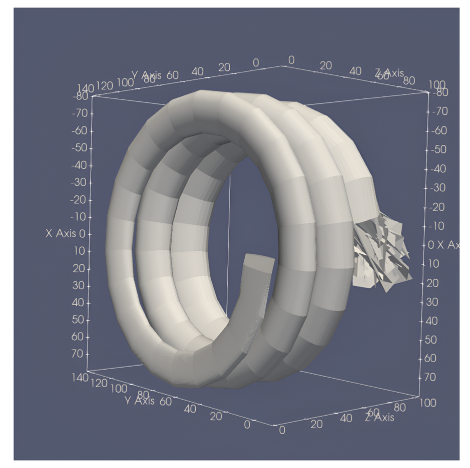
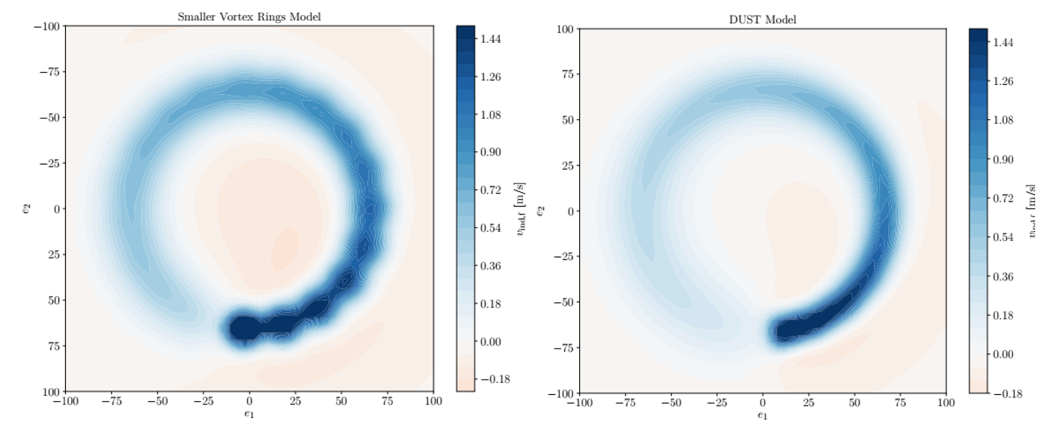
Methodology

- Vortex ring orientation and strength is based on lifting-line theory for elliptical wings

- Vortex ring shedding under the assumption of rigid convection at wind speed

- Vortex ring radius chosen heuristically to match analytic solution[1] in the axisymmetric case and then validated against higher-fidelity simulator *DUST*[2] (vortex-lattice)





- Flight trajectory optimization of dual-wing AAA system including implicit wake model by transcribing to and solving the nonlinear program (NLP) using our own software *AWEbox*

$$\begin{aligned} \min_{w} \quad & f(w) \\ \text{s.t.} \quad & g(w) = 0, \\ & h(w) \geq 0\,. \end{aligned}$$

Sources

[1]Trevisi, F., Riboldi, C., Croce, A. (2023) Vortex model of the aerodynamic wake of airborne wind energy systems, Wind Energy Science (8) 999-1016.

[2]Tugnoli, M., Montagnani, D., Syal, M., Droandi, G., & Zanotti, A. (2021). Mid-fidelity approach to aerodynamic simulations of unconventional VTOL aircraft configurations. Aerospace Science and Technology, 115, 106804.