Rigid-Wake Lifting-Line Vortex Modeling in a Single-Kite AWE Optimal Control Problem

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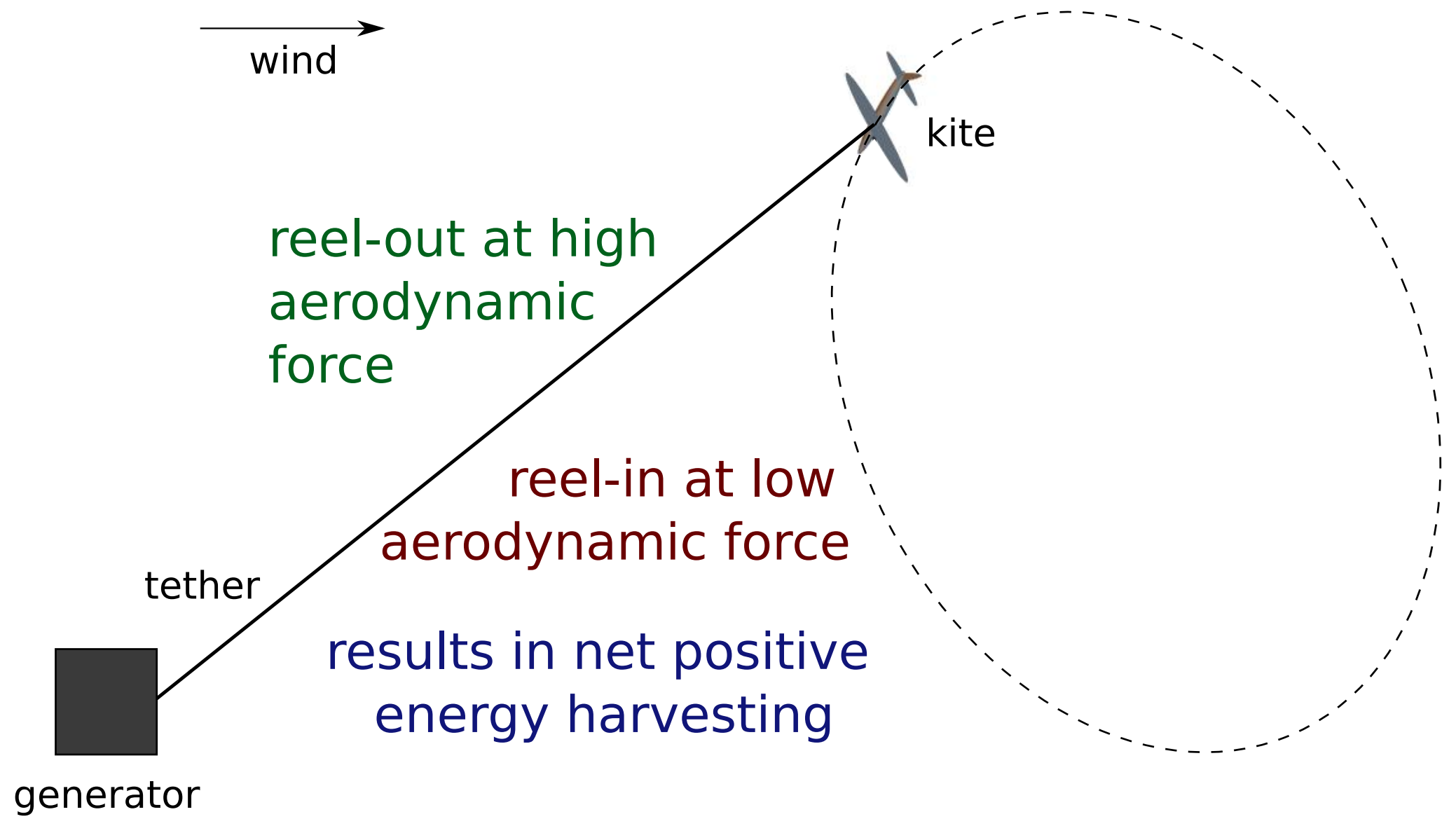
Airborne Wind Energy (AWE) systems can react quickly to demand or grid requirements.



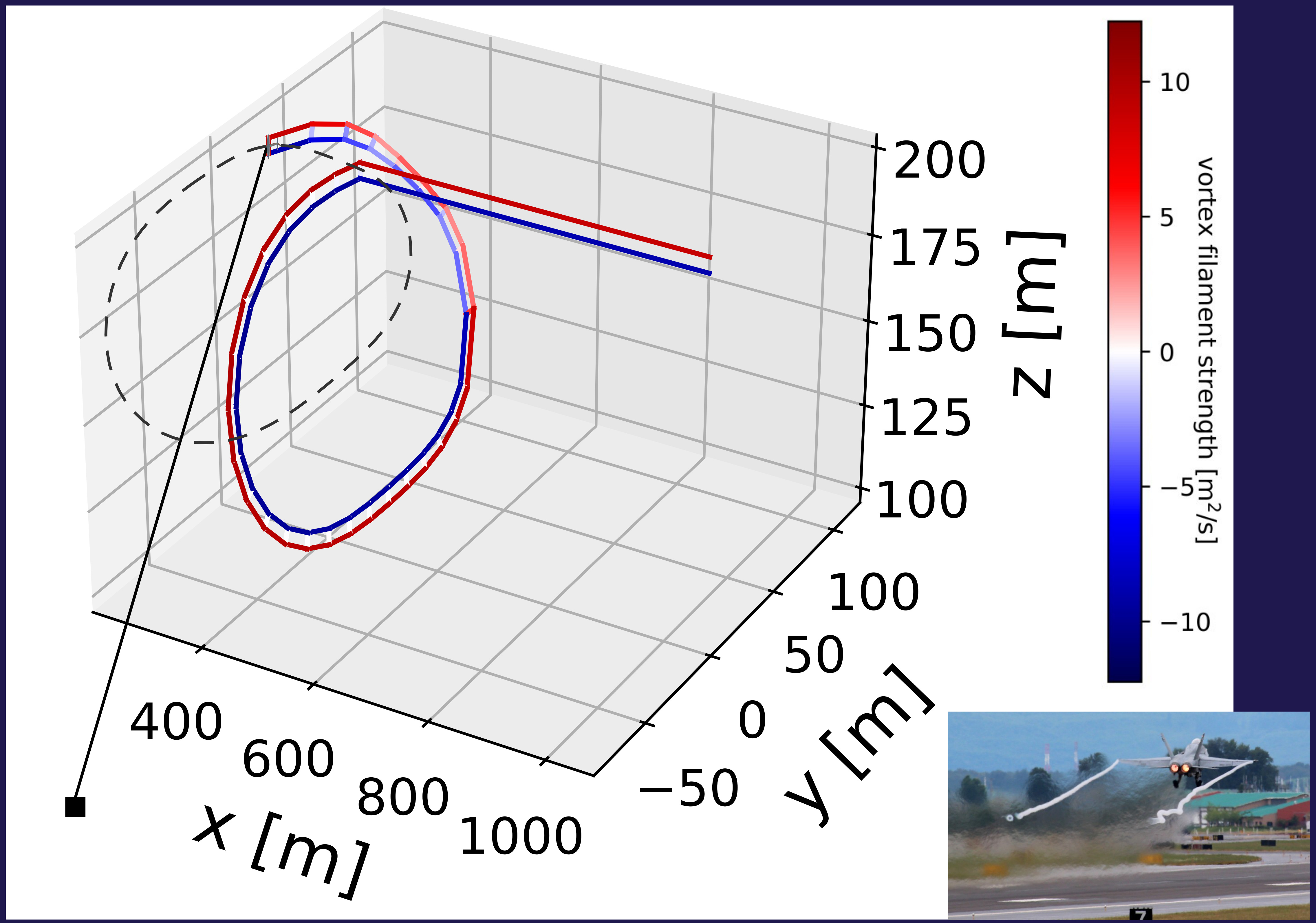
We can predict the system performance – e.g., during initial design phases or financing – by solving Optimal Control Problems (OCP) like

$$
\begin{aligned}
\underset{x(\cdot),\, u(\cdot),\, \theta,\, T}{\text{minimize}} \quad & -\frac{1}{T}\int_0^T \frac{P(t)}{\pi R^2}\mathrm{d}t \\
\text{subject to} \quad & F(\dot{x}(t), x(t), u(t), \theta) = 0,\ \forall t \in [0, T], \\
& h(x(t), u(t), \theta) \geq 0,\ \forall t \in [0, T], \\
& x(0) - x(T) = 0
\end{aligned}
$$

Such a prediction can only be as good as the model used in the OCP, including the model of the momentum transfer in the disturbed flow (the wake). One way to describe fluid's behavior is to model the sources of circular-motion in the flow (vortex).

What happens if we include a rigidly-convected lifting-line vortex model in a single-kite AWE OCP?

In single-kite **airborne wind energy** optimal control problems, we only need to include **a small amount of fluid history** for a good description.



(center) Snapshot of a power-optimal single-kite AWE system, showing the wake modeled with rigidly-convected vortex filaments, shed from the kite's lifting-line. This image show the case of 30 control intervals, one period of a resolved 'near' wake, and a 'far' wake that conserves circulation. (bottom right) Photo of vortices shed from a plane at take-off. Photographer: Eric Prado)

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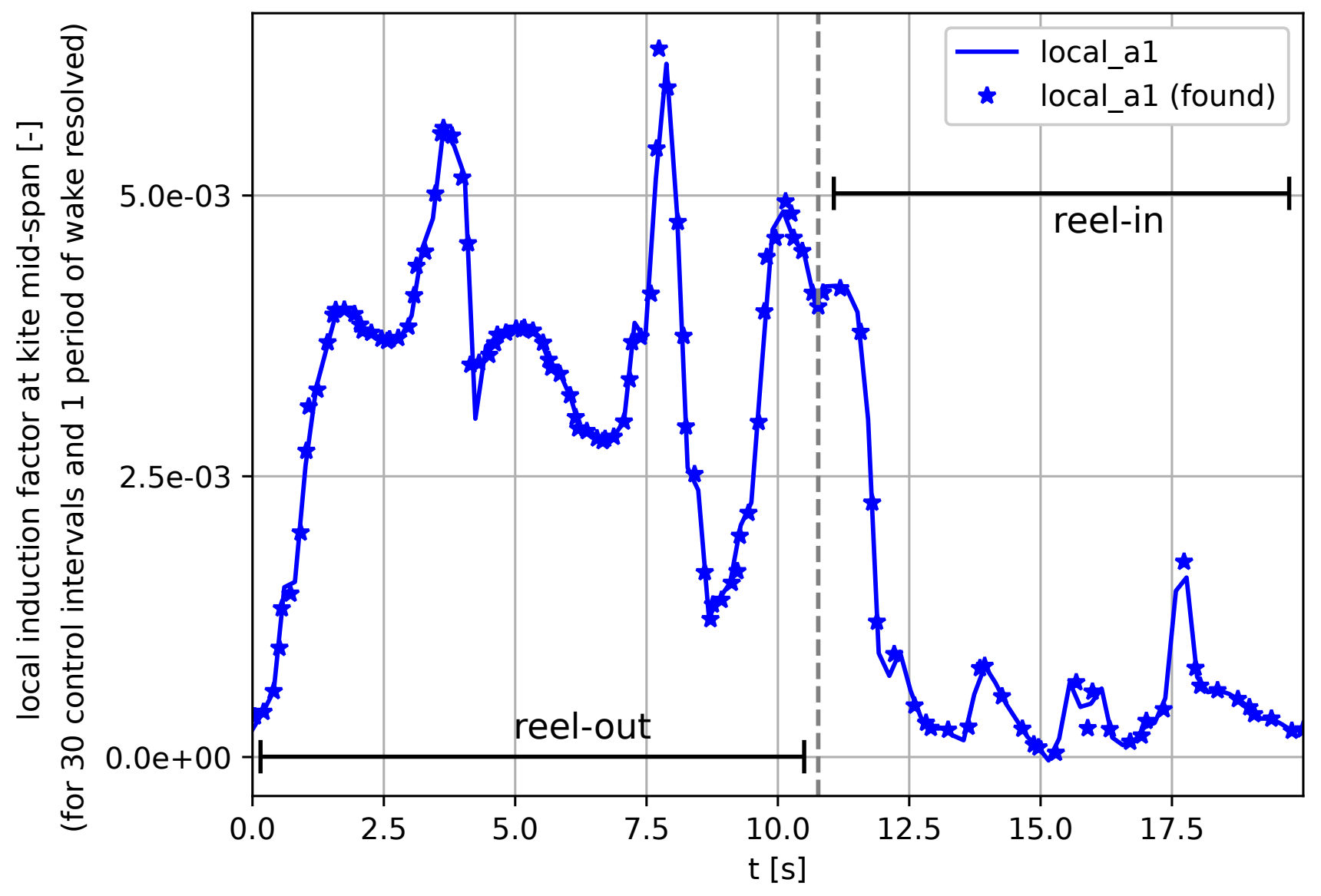
Formulate and solve in `awebox`

Atmosphere International Standard Atmosphere
Wind Log Wind Profile with 5m/s wind speed at 10m height
Kite 6 DOF model of the Ampyx AP2, attached at COM, in lift-mode operation
Other time period between 5 and 20s, and fixed tether diameter of 2cm

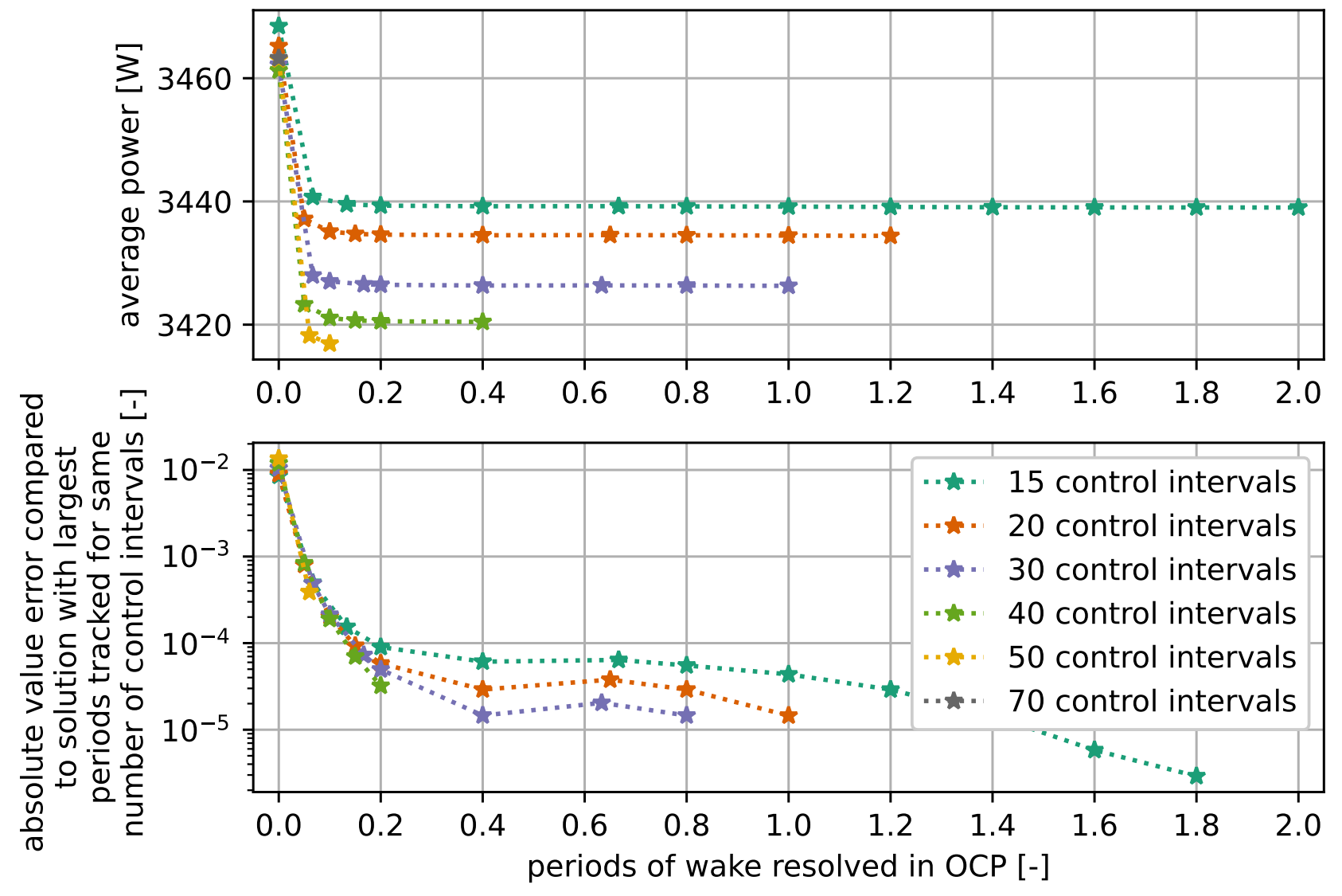
Model Constraints
maximum tether force,
maximum airspeed,
maximum angle of attack and sideslip,
maximum rotational velocity,
minimum tether force,
minimum airspeed,
minimum angle of attack and sideslip.

OCP Discretized with Radau direct collocation of order 4, using zero-order-hold controls and single-reelout phase-fixing. One-winding initialization by homotopy.

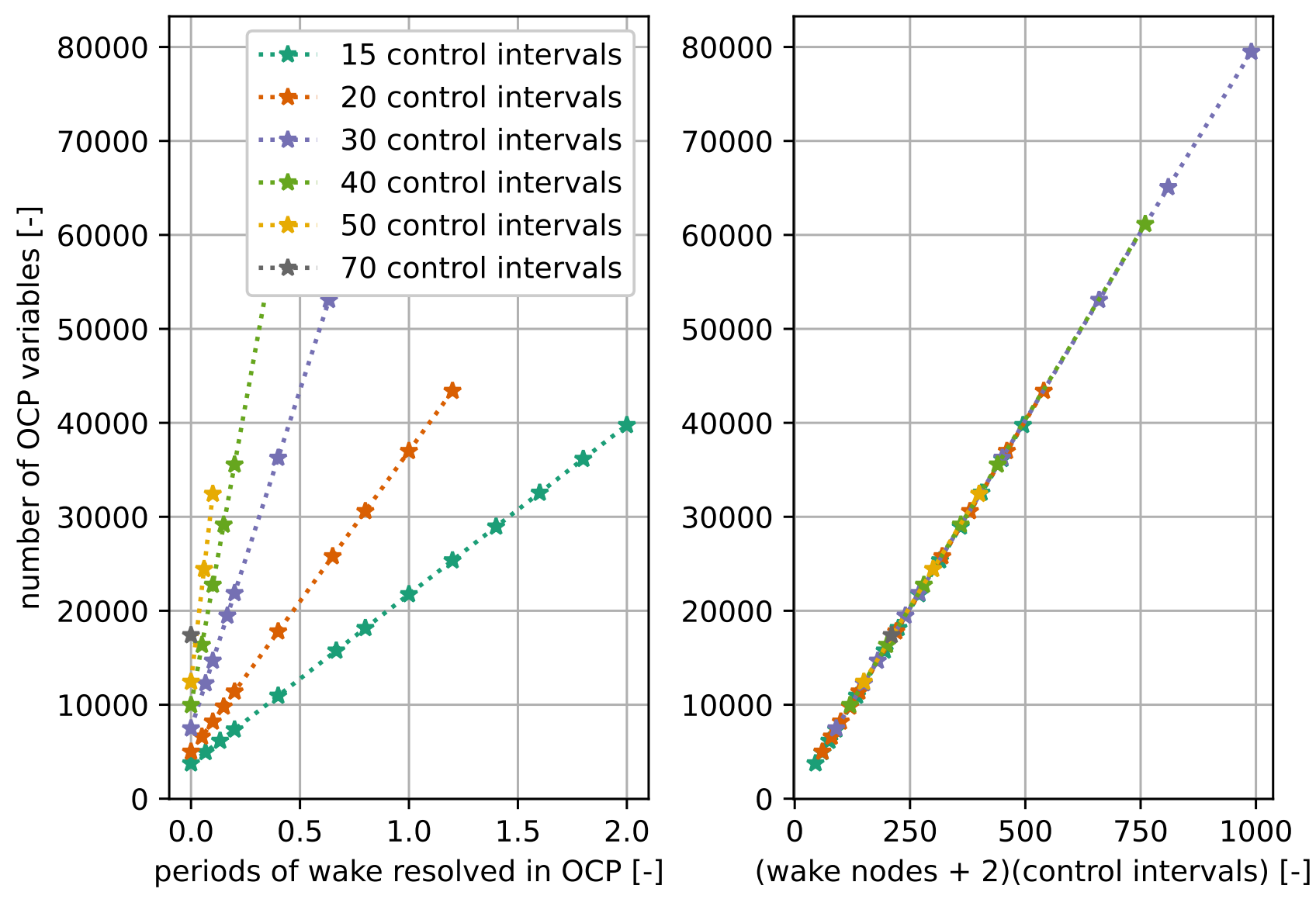
the high aerodynamic force (reel-out) period changes the flow's momentum more than the low aerodynamic force (reel-in) period



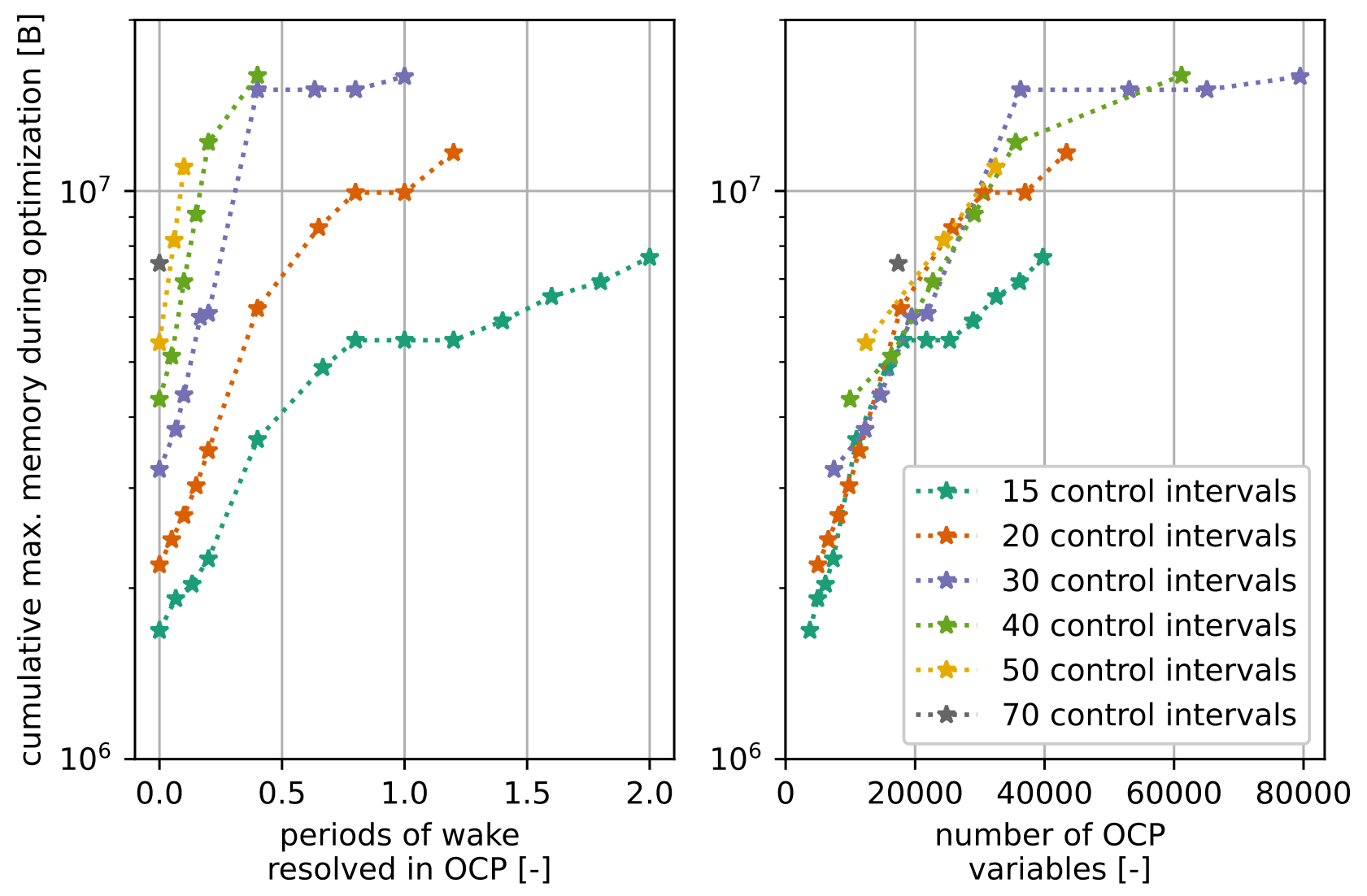
for a single-kite OCP, most of the impact of wake is included when the newest 20%-of-a-period of wake is resolved



problem size grows with number of wake nodes and control intervals



before multi-threading memory management takes over, memory scales logarithmically with problem size



Literature

[3] de Schutter, J., et al. (2023). AWEbox: An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems. Energies, 16(4).