

Pumping cycle optimization of soft-wing airborne wind energy systems using quasi-steady simulations

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Abstract. This study presents a quasi-steady simulation and optimization framework for ground-generation airborne wind energy systems with soft kites. A novel parameterization of the reel-out phase is introduced, explicitly resolving crosswind maneuvers through a kinematically feasible figure-of-eight trajectory, thereby improving physical representativeness compared to conventional averaged crosswind models. The framework is validated against experimental data from the TU Delft V3 reference kite, showing good agreement in kite kinematics, phase- and cycle-averaged power, while highlighting expected limitations in instantaneous force prediction. The model is subsequently used to optimize pumping-cycle operational parameters under fixed environmental conditions, revealing significant variations in cycle duration and modest gains in average power. The results demonstrate the suitability of the proposed framework for efficient conceptual design studies and operational optimization of airborne wind energy systems.

1. Introduction

A fast and sufficiently accurate estimation of the power output of airborne wind energy systems (AWES) during the conceptual design phase is crucial for the technical feasibility, economic viability, and commercial success of the technology [1]. To this end, this study presents and evaluates a mid-fidelity modeling framework for estimating the net power output of soft-kite, ground-generation AWES.

During pumping operations, the force balance of high surface-to-mass ratio wings, such as soft kites, is dominated by aerodynamic loads and tether tension, while gravitational effects remain secondary [2]. Furthermore, the characteristic timescale of the underlying dynamics is typically much shorter than that of the flight maneuvers executed over an entire pumping cycle. Consequently, particularly in system-level design and optimization studies, modeling the flight operation as a sequence of quasi-steady states can provide valuable insight into pumping-cycle power production while maintaining a limited computational burden [1].

Quasi-steady model implementations vary considerably in the literature. Early analytical frameworks for crosswind flight neglected mass to simplify the governing equations [3, 4]. Including weight precludes a direct analytical solution for the quasi-steady equilibrium and instead requires iterative numerical procedures [2, 5]. Furthermore, the interpretation of quasi-steadiness itself is not uniform across the literature. Some formulations neglect all accelerations to achieve a fully static equilibrium at each time step [2, 6]. In contrast, other models adopt a partial approach: Schmehl et al. neglect tangential and radial accelerations [5], while Cayon et al. only omit tangential acceleration [7].

In this study, we build upon the method presented in [2, 6], and represent the kite as an inertia-free point mass. The kite is operated along a sequence of steady-states on predefined trajectories during the three phases of the pumping cycle: reel-out, reel-in, and transition. Previous simulation frameworks adopting this quasi-steady formulation relied on a simplified representation of the reel-out phase, typically based on an average crosswind-state description governed by synthetic parameters calibrated using experimental data or higher-fidelity dynamic simulations [2]. While effective for analyzing existing systems, this reliance on tuned parameters limits the applicability of such frameworks when evaluating new system designs.

The present study aims to address this limitation by introducing a more realistic description of the reel-out phase, in which the crosswind maneuvers are explicitly resolved within the quasi-steady framework. A similar strategy was explored in Ranneberg et al. for the Enerkite semi-rigid wing [8]. The impact of this addition to the formulation presented in [2] will be tested by comparison against experimental data from the TU Delft V3 reference kite, hereafter referred to as V3 kite [9]. Finally, an optimization problem aiming to maximize the average pumping-cycle power will be formulated and solved leveraging the described simulation framework.

The primary contribution of this work is the development of a quasi-steady simulation framework that replaces the use of averaged parameters for the reel-out phase with an explicit, kinematically feasible figure-of-eight trajectory parameterization. By resolving crosswind maneuvers while respecting physical steering limits, the model provides a more physically representative estimation of power output for soft-kite systems. The limited computational burden of the presented framework makes it suitable for conceptual design and the exploration of large operational parameter spaces.

The remainder of the paper is organized as follows: Sect. 2 describes the quasi-steady simulation model, focusing on the novel flight path parameterization for the reel-out phase. Section 3 presents a thorough validation of the simulation framework against experimental data. Section 4 outlines the optimization problem, and Sect. 5 presents the optimization results. Conclusions are drawn in Sect. 6.

2. Quasi-steady simulation of the pumping cycle

The pumping cycle representation analyzed in this study consists of three distinct phases: reel-out (RO), reel-in (RI), and the transition between reel-in and reel-out (RIRO). The

reel-out to reel-in (RORI) transition is not modeled, as its contribution to cycle power and duration is negligible [2].

For the RI and RIRO phases, simplified planar trajectories flown in the zero-azimuth plane are computed as described in [2]. In contrast, the present study introduces an explicit parameterization of the crosswind maneuvers flown during RO. In particular, we are using Lissajous math to represent the figure-of-eight trajectories. Accordingly, a figure-of-eight pattern centered on an axis inclined by an angle θ_{avg} with respect to the ground plane, can be defined as:

$$\begin{cases} \phi(s) &= \phi_{\text{max}} \sin(\pi s) \\ \theta(s) &= \theta_{\text{avg}} + \theta_{\text{rel}} \sin(2\pi s) \end{cases} , \quad (1)$$

where $\{\phi, \theta\} : \mathbb{R} \rightarrow \mathbb{R}$, $s \mapsto \{\phi(s), \theta(s)\}$ denote the instantaneous azimuth and elevation angles as functions of the non-dimensional arc-length parameter s , which specifies the kite position along the trajectory. The parameters ϕ_{max} and θ_{rel} define the maximum azimuthal and relative elevation excursions, respectively, thereby bounding the kite's flight envelope.¹ The corresponding course angle χ is computed as $\chi(s) = -\frac{\partial \phi / \partial s}{\partial \theta / \partial s}$.

The control strategy implemented in the simulation framework is designed to reproduce the main characteristics of real-flight operation while remaining consistent with the quasi-steady assumption. During each phase of the pumping cycle, the kite is assumed to fly at a constant angle of attack, corresponding to the design trim condition, such that the aerodynamic coefficients remain constant along the trajectory. Under this assumption, the aerodynamic forces depend only on the apparent wind velocity.

During RO and RIRO, a constant reel-out speed is prescribed, whereas during RI a constant tether force is imposed. At each point along the trajectory, the inertia-free, quasi-steady equilibrium is solved iteratively to determine the unknown quantities, namely: the kite tangential speed (for all phases); the tether force (during RO and RIRO); and the (negative) reel-out speed (during RI). The resulting kite velocity is subsequently used to update the kite position along the prescribed trajectory [2].

3. Validation of the simulation framework on experimental data

The accuracy of the quasi-steady modeling framework has been evaluated in previous studies, showing reasonable agreement with experimental data [6]. In this work, the validation is repeated to assess the impact of the proposed reel-out trajectory parameterization and the improved identification of system properties.

The V3 kite is used as reference for validation, as its physical and aerodynamic properties are well documented in the literature [10–14]. Although the V3 kite was originally designed for a 20 kW demonstrator, the 100 kW Kitepower B.V.² ground station was used during the experimental campaign [9]. The main design properties of the system are reported in Table 1. The kite was flown automatically through an

¹The algebraic signs of θ_{rel} and ϕ_{max} determine whether the kite performs down- or up-loops and the starting point along the trajectory, respectively.

²URL: <https://thekitepower.com/>. Visited on 23/02/2026

airborne kite control unit (KCU) with actuators pulling on the powering and steering lines. The experimental flights were conducted under conservative operational settings, as they were primarily aimed at data acquisition rather than power production. As a result, the measured power output is not representative of the current performance of Kitepower systems of similar size.

Table 1. Wing-KCU assembly and tether properties.

Symbol	Definition	Value	Unit
A	Total wing area	25	m ²
S	Projected wing area	19.75	m ²
m	Total airborne mass	36.2	kg
ρ_t	Tether material density	724	kg m ³
d_t	Tether diameter	10	mm

3.1. Environmental conditions and system’s properties identification

Experimental data were collected during a three-hour flight on 8 October 2019 at the former naval air base of Valkenburg, Netherlands (52° 10’ N, 4° 26’ E). The system completed 87 pumping cycles under moderate wind conditions, see Fig. 1. The validation presented in this study focuses on the reference pumping cycle defined by Schelbergen et al. [6], corresponding to the 73rd cycle. This cycle was selected because it exhibits neither anomalies in wind conditions nor irregularities in system operation or performance.

To enable a meaningful comparison between experimental measurements and quasi-steady simulation results, the simulation framework is configured to reproduce the effective operating conditions of the selected pumping cycle, within the constraints imposed by the prescribed flight-path parameterization. This requires the identification of the environmental conditions, system physical properties (in particular the aerodynamic coefficients), and operational parameters (such as reel-out speed, reel-in force, and reel-out pattern) corresponding to the experimental flight.

Environmental conditions and system properties are identified using an extended Kalman filter (EKF) applied to the experimental data [10]. Figure 1a shows the estimated vertical wind profile. Data points corresponding to straight-flight segments (yellow markers) during RO and RI are distinguished from turning states (gray markers), for which increased sideslip leads to higher uncertainty in the estimated horizontal wind speed. Accordingly, only straight-flight data are used to fit a neutral logarithmic wind profile. The fitted profile features a roughness length of 0.1 m and a reference wind speed of 5.65 ms⁻¹ at 6 m height. Wind speed statistics measured at the ground station anemometer, mounted on a 6 m mast, are reported as a box-and-whisker plot in the same panel.

Figure 1b presents the estimated horizontal wind speed at kite altitude together with the measured kite elevation, showing a consistent increase of wind speed with altitude, in agreement with the identified shear profile. The estimated aerodynamic coefficients are shown in Fig. 1c, with phase transitions indicated by vertical dashed lines; the average

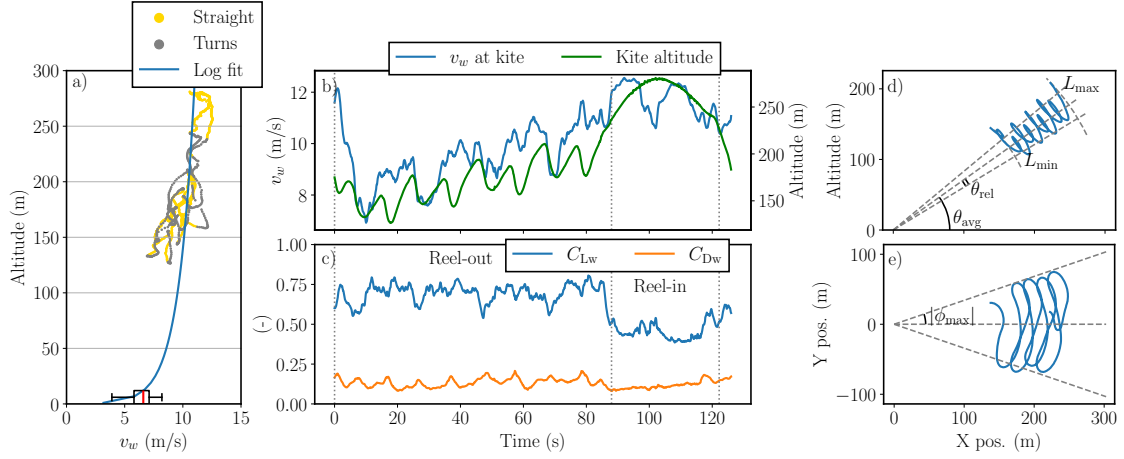


Figure 1. Environmental conditions and system's properties identification for the 73rd cycle. a) Vertical wind profile estimation and corresponding logarithmic fit. b) Estimated horizontal wind speed at kite and measured kite altitude. c) Estimated aerodynamic coefficients for the wing. d) & e) Identification of the QSM-simulation reel-out pattern parameters.

Table 2. Identified aerodynamic coefficients for the reference cycle.

Symbol	Definition	Value	Unit
$C_{Lw,RO}$	Wing lift coefficient (powered state)	0.68	-
$C_{Lw,RI}$	Wing lift coefficient (depowered state)	0.45	-
$C_{Dw,RO}$	Wing drag coefficient (powered state)	0.14	-
$C_{Dw,RI}$	Wing drag coefficient (depowered state)	0.11	-
C_{Dp}	Parasitic drag coefficient (powered & depowered state)	0.045	-

lift and drag coefficients for the powered and depowered wing states are summarized in Table 2. The wing drag coefficient is corrected to account for parasitic drag contributions from the KCU and bridle lines [7]. The reel-out speed prescribed during RO and RIRO and the tether force imposed during RI are set equal to the corresponding phase-averaged experimental values. Finally, Fig. 1d and Fig. 1e illustrate the identification of the reel-out trajectory parameters used in the simulation, reported in Table 3. The reel-out phase is identified based on a threshold in reel-out speed, defining the initial tether length $L_{\min}$, while its end corresponds to the maximum tether length $L_{\min} + \Delta L_{RO}$. Angular parameters are obtained from the elevation and azimuth time series between these instants by extracting peaks and valleys, yielding θ_{avg} , θ_{rel} , and ϕ_{max} .

3.2. Validation results

Figure 2 compares experimental and simulated time series of tether length, reel-out speed, tether force, and kite kinematics for the reference pumping cycle.

The overall kite kinematics during reel-out are well captured by the simulation, despite the limited number of parameters used to describe the prescribed trajectory. The duration of the reel-out phase is well matched. However, a delay gradually accumulates

Table 3. Reel-out pattern parameters.

Symbol	Definition	Value	Unit
θ_{avg}	Average elevation angle during reel-out	35.5	deg
θ_{rel}	Relative elevation angle during reel-out	4.3	deg
ϕ_{max}	Maximum azimuth angle during reel-out	18.9	deg
L_{min}	Tether length at the start of reel-out	201.6	m
ΔL_{RO}	Reel-out stroke length	103.8	m

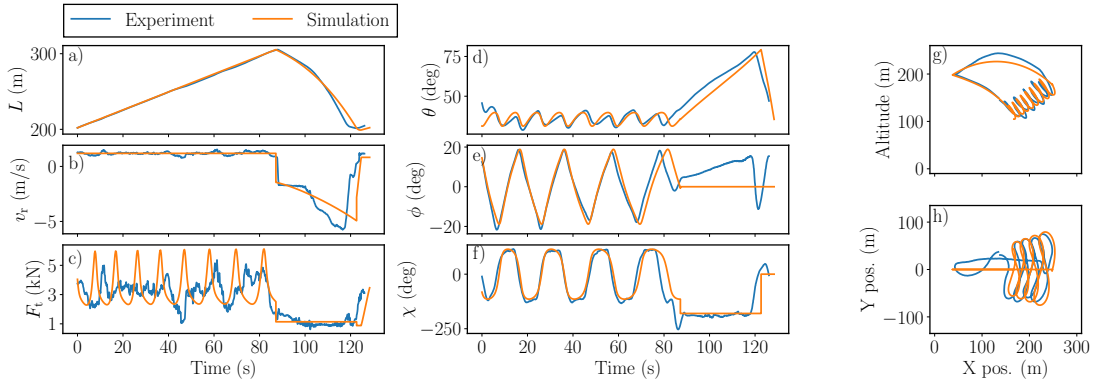


Figure 2. Comparison between experimental and simulated reference cycle. a) Tether length. b) Reel-out speed. c) Tether force at ground station. d) Elevation angle. e) Azimuth angle. f) Course angle. g) XZ-projection of the flight trajectory. h) XY-projection of the flight trajectory.

during the last figure-of-eight maneuver, resulting in a different final spatial position of the kite, as visible in the elevation θ , azimuth ϕ , and course χ angle time series. The limitations of the simplified reel-out trajectory are most evident at the beginning of the pumping cycle, where the transition from reel-in to reel-out is not explicitly modeled. While the initial azimuth angle is matched, this leads to mismatches in elevation and course angles, which are also apparent in the planar trajectory projections. Furthermore, the experimental reel-out pattern exhibits a slight asymmetry in elevation, which cannot be reproduced by the Lissajous parameterization of Eqs. (1).

The simulated tether force shows noticeable discrepancies, related to modeling assumptions in the quasi-steady framework: (i) inertial and centrifugal effects are neglected, (ii) the angle of attack and aerodynamic coefficients are assumed constant along the trajectory, and (iii) unsteady wind fluctuations are not modeled, although wind shear is included.

Previous studies indicate that the exclusive inclusion of inertial and centrifugal effects in quasi-steady formulations has a limited influence on the predicted tether force trends [7, 15]. Therefore, neglecting these effects alone is unlikely to explain the discrepancies observed in the force peaks. The flight analyzed in this work was performed using an over-sized KCU, whose mass and inertia affect the trim condition of the kite and can induce larger variations in angle of attack during the loop. Under these conditions, inertial effects may become more relevant through their coupling with the aerodynamic state

of the system. However, previous analyses show that their influence on the maximum tension peaks remains limited [7].

These observations indicate that improving the aerodynamic representation, specifically through angle-of-attack-dependent lift and drag coefficients, is the most important step toward increasing the fidelity of quasi-steady formulations [7]. Finally, because turbulence is not explicitly resolved, the simulated tether force remains smooth and idealized, lacking the stochastic variability observed in the experimental measurements.

The reel-in phase is more challenging to capture accurately. The combined assumptions of constant ground tether force and constant angle of attack result in a reel-in speed that differs from the experimental one, leading to an overestimation of the reel-in duration. In terms of angular kinematics, the largest discrepancies are observed in the azimuth angle, which arise from the simplified two-dimensional reel-in trajectory constrained to the zero-azimuth plane. The abrupt changes observed in the angular quantities at the transitions between phases, particularly in the course angle, are an inherent consequence of the framework formulation: once the switching conditions are met, the kite state is instantaneously reoriented and powered or depowered to initiate the subsequent phase.

Figure 3 presents the time series of the mechanical power extracted over the pumping cycle. For the experimental reference cycle, two power signals are shown: the direct measurement from the winch, P_m^* , and the mechanical power computed as product of reel-out speed and tether force, $P_m = F_t v_r$. The reel-out speed and tether force are respectively plotted in Fig. 2b and Fig. 2c. The winch power measurement is filtered using a moving average over 10 samples. During the reel-out phase, the two experimental power signals are in close agreement. In contrast, during the reel-in phase, significant discrepancies are observed. To ensure consistency in the comparison with the simulation results, the simulated mechanical power is compared against the experimentally derived power computed as the product of reel-out speed and tether force (blue and orange lines, respectively).

The average mechanical power is computed for each phase of the pumping cycle, as well as over the entire cycle, and reported in the histogram in Fig. 3b. The simulation slightly over-predicts both the reel-out and reel-in power. Even though the experimental flight phases have been redefined to match the cycle representation adopted in the simulation framework, the transition phase still exhibits a substantial mismatch, as also reported in previous validation studies [6]. However, since the transition phase is of short duration, its contribution to the overall cycle energy is limited. As a result, the total cycle-averaged power is under-predicted by approximately 7%.

4. Pumping cycle optimization

Building on the quasi-steady simulation framework, an optimization problem is formulated to identify the set of operational parameters that maximizes the average pumping-cycle power under a given environmental condition:

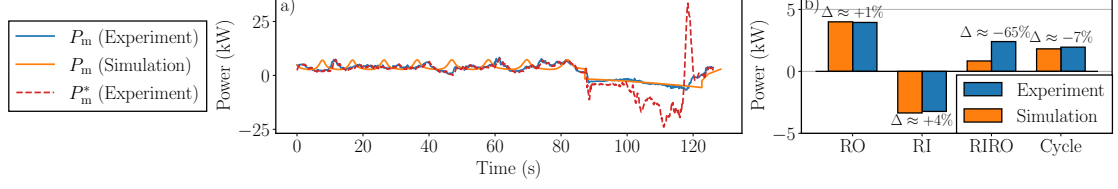


Figure 3. Comparison between experimental and simulated reference cycle. a) Mechanical power calculated as product between tether force and reeling speed P_m , and as measured by the winch P_m^* . b) Average mechanical power per phase and per cycle, and corresponding relative percentage error.

$$\max \left(\frac{P_{\text{cycle}}(v_{\text{rRO}}, F_{\text{tRI}}, \theta_{\text{avg}}, \theta_{\text{rel}}, \phi_{\text{max}}, L_{\text{min}}, \Delta L_{\text{RO}})}{\frac{1}{2} \rho_a v_w^3 S} \right), \quad (2)$$

where P_{cycle} denotes the average power over one pumping cycle, and ρ_a and v_w are the air density and wind speed at the reference height of 100 m.

The decision variables include the reel-out speed and reel-in force setpoints, v_{rRO} and F_{tRI} ; the reel-out trajectory angles θ_{avg} , θ_{rel} , and ϕ_{max} , the minimum tether length L_{min} and the stroke length ΔL_{RO} . The decision variables are bounded through box constraints reflecting the physical and design limits of the kite, tether, ground station, and control system under consideration.

In addition to the box bounds, the optimization is subject to operational and safety constraints. To avoid saturation of the reel-out force limit, the reel-out speed setpoint must remain effective throughout the reel-out phase, and the resulting tether force must not exceed the admissible maximum:

$$\max(v_{\text{rRO}}) \leq \bar{v}_{\text{rRO}} \text{ and } \max(F_{\text{tRO}}) \leq F_{\text{max}}. \quad (3)$$

To maintain control authority and avoid reel-out during reel-in, we impose:

$$\min(F_{\text{tRI}}) \geq \bar{F}_{\text{tRI}} \text{ and } \max(v_{\text{rRI}}) \leq 0. \quad (4)$$

Safe and realistic flight operation is enforced by requiring a minimum number of crosswind patterns during reel-out, $N_{\text{cwp}} \geq N_{\text{cwp,min}}$, by limiting the maximum tether length, $L_{\text{min}} + \Delta L_{\text{RO}} \leq L_{\text{safe}}$, by preventing excessive overflight of the ground station $\max(\theta) \leq \theta_{\text{max,RI}}$, and by imposing a minimum operational altitude for the kite.

Actuation and control limits are enforced by bounding the course rate along the reel-out trajectory. Hence, the kite's turning capabilities are explicitly accounted for in the flight-path definition. The resulting trajectory respects the physical constraints of the steering system and is therefore kinematically feasible.

5. Results

The optimization framework outlined in Sect. 4 is first applied to the system described in Sect. 3 loaded under the same wind profile as the reference cycle. The aerodynamic

properties of the wing are the same as those in Table 2, aiming to only isolate the impact of optimization of the operational parameters on the pumping cycle and, consequently, on the cycle power. Even after optimization, the cycle power remains limited and does not reflect the potential of a commercial system of the same size, due to the very conservative design choices of the V3 kite.

The numerical values for the box constraints are reported in Table 4. Some were derived from previous studies, while the remaining values were set based on the authors' informed judgment. In addition, we set a minimum of one crosswind maneuver during reel-out, a maximum safety tether length L_{safe} of 307 m, a maximum elevation angle during reel-in θ_{maxRI} of 100 deg, a maximum course rate χ_{max} of 1.23 rad/s, and a minimum operational altitude h_{min} of 20 m.

The optimization problem presented in Sect. 4 was solved using Scipy's Sequential Least Squares Programming (SLSQP) implementation. The stopping criterion tolerance and Jacobian numerical approximation step were set to 10^{-6} [16]. Starting from the reference simulation of Sect. 3, the optimization process converged in 5 iterations, taking approximately 164 seconds on an Intel® Core™ i7-8565U CPU.

Figure 4 shows the results of the pumping cycle optimization, compared with the simulated reference cycle discussed in Sect. 3. The optimal pumping cycle is substantially shorter than the baseline reference, with the largest contribution arising from the reel-out phase. This reduction is primarily due to the shorter tether stroke length, as shown in Fig. 4a, where reel-out starts from a longer tether length but ends at the same maximum length as in the baseline case. The reel-out stroke length and the reel-out average elevation angle of the optimal solution reach their lower bound, as highlighted in Table 4 by the rectangular boxes indicating the active constraints.

In addition, the optimal solution features a slightly higher reel-out speed, which is evident both from the steeper slope in the initial portion of Fig. 4a and from the reel-out speed time series in Fig. 4b. This moderate increase in reel-out speed consistently leads to a lower tether force during the reel-out phase. As a result of these combined effects, the average reel-out power increases by approximately 10% compared to the baseline case, as illustrated in the histogram in Fig. 4e. The reel-in duration is less impacted. In fact, the shorter tether length to be reeled in and the lower reel-in force (hitting the lower bound of Table 4) yield a lower reel-in speed and a consequent substantial reduction in power of about 39 %, see Fig. 4e. During the RIRO phase, the optimizer converges to a zero-power transition, with a large relative difference. Nevertheless, due to the very short duration of the RIRO transition, the contribution to the cycle power is limited. The overall cycle power increases by about 6 %, reaching 1.9 kW.

Table 4. Box constraints and optimal solution under the reference cycle loading condition.

Decision variables	v_{rRO}	F_{tRI}	θ_{avg}	θ_{rel}	ϕ_{max}	L_{min}	ΔL_{RO}
Lower bound	-9.8 m/s	1 kN	35 deg	4 deg	15 deg	180 m	90 m
Upper bound	9.8 m/s	8.8 kN	60 deg	10 deg	40 deg	240 m	115 m
Optimal solution	1.35 m/s	1 kN	35 deg	4.3 deg	24 deg	217 m	90 m

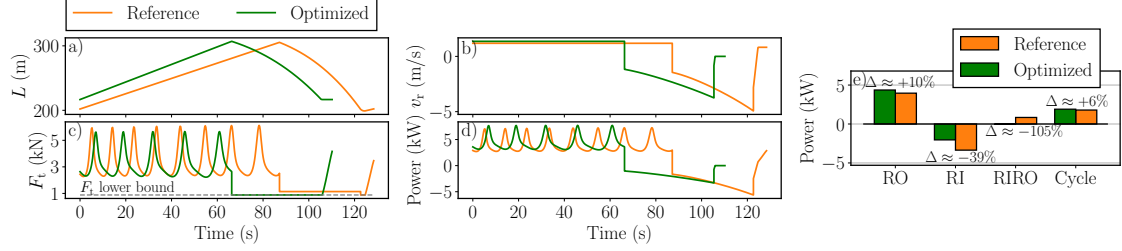


Figure 4. Comparison between the simulated reference cycle and the optimized pumping cycle under the same loading condition. a) Tether length. b) Reel-out speed. c) Tether force at ground station. d) Mechanical power. e) Average mechanical power per phase and per cycle, and corresponding relative percentage increase.

6. Conclusion

This study introduced an enhanced quasi-steady modeling framework for ground-generation airborne wind energy systems by proposing a more realistic parameterization of the reel-out trajectory. Unlike previous quasi-steady approaches, the proposed formulation explicitly resolves the crosswind maneuvers during reel-out through a kinematically feasible figure-of-eight trajectory, thereby linking the turning behavior of the wing directly to the flight path definition. This improvement increases the physical representativeness of the model while preserving the computational efficiency required for conceptual design and system-level optimization studies.

Validation against experimental data from the TU Delft V3 reference kite showed good agreement in terms of phase-averaged quantities and overall cycle power. As expected, neglecting inertial effects in the quasi-steady formulation leads to discrepancies in instantaneous tether force predictions, particularly regarding peak amplitudes.

While these instantaneous peaks are critical for structural fatigue analysis and component sizing, they are of secondary importance during early-stage design. At this phase, the primary objective is the rapid exploration of the parameter space to maximize energy yield. Consequently, the quasi-steady approach remains a computationally efficient and valid tool, as its limitations have a limited impact on the cycle-averaged performance metrics used to drive optimization.

The proposed simulation-based optimization framework was applied to the V3 kite to identify operational parameters that maximize average cycle power. The results revealed substantial variations in optimal cycle duration and operational settings relative to a baseline reference cycle, while yielding a modest increase in average power. These findings highlight the trade-offs between trajectory design, reeling strategy, and power production, and demonstrate the capability of the framework to explore the operational design space efficiently.

Future work shall focus on a fully symbolic implementation of the model and its associated simulation and optimization framework, with the aim of further reducing computational cost in large-scale optimization studies. In addition, the framework will be extended to derive the full system power curve across a wide range of wind condi-

tions, supporting its application in conceptual design and techno-economic assessments of airborne wind energy systems.

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