

# Optimal Flight Pattern Debate for Airborne Wind Energy Systems: Circular or Figure-of-eight?

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**Abstract.** The computational study compares the performance of circular and figure-of-eight flight patterns for fixed-wing ground-generation airborne wind energy (AWE) systems using a PID-based basic controller that effectively controls the kite during each patterns pumping cycle in a Matlab<sup>®</sup> Simulink<sup>®</sup> environment. A simple, adjustable control framework enables a steady analysis within consistent operational parameters, allowing for fair comparisons of power output, power quality, ground surface area requirements, and structural load impacts. Unlike for small lightweight kites, the simulation results reveal that using the 150 m<sup>2</sup> MegAWES reference kite, the power is not similar over different patterns. The circular flight pattern achieves the highest cycle-averaged power output, providing 1.85 MW at a power density of 2.94 MW km<sup>-2</sup>, making it advantageous for maximising energy within limited spatial constraints. Conversely, the figure-of-eight down-loop pattern demonstrates superior power quality with lower power peaks and lower expected structural fatigue due to a reduced cyclic aerodynamic load frequency and amplitude, supporting greater operational stability and system longevity. The figure-of-eight up-loop performed the worst on all metrics considered in this work. This study offers insights into the trade-offs between energy output, efficiency, and structural demands associated with each flight path, providing a foundation for future AWE flight path selection and control strategy optimisations.

## 1 Introduction

Airborne wind energy (AWE) is an emerging renewable energy technology aiming to harness the power available in higher-altitude winds. Unlike conventional wind turbines, the operating pattern is not fixed. A conventional wind turbine has rotating blades connected to a hub. AWE devices use tether kites, which have a much larger potential operating domain, which allows for better adaptation to the available wind resource but comes with complex controller challenges.

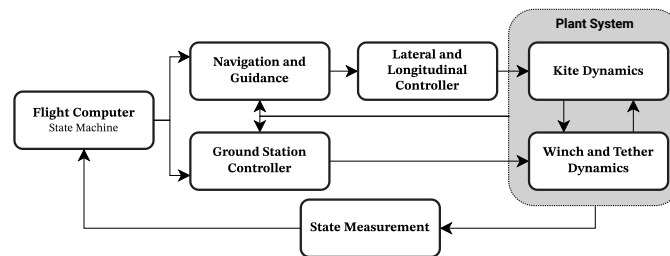
One shared characteristic of the different existing AWE systems is that they all fly in a closed pattern. However, the best shape of this pattern has not yet been decided on. The debate about the optimal flight pattern dates back to the beginning of the technology development in the first decade of the 21st century. The industry appears undecided on a single specific pattern, with circular and figure-of-eight paths both prevalent. Tether winding is mentioned as one of the key reasons for the latter (Houska and Diehl, 2006; Licitra et al., 2019). Other factors might also influence the choice, as discussed in this study.

In particular, three main patterns are currently flown in AWE. These are divided into two shapes: a circle and a figure-of-eight. The latter can be flown in two directions, one where the outer segments of the figure are flown upwards (up-loop) and one where they are flown downwards (down-loop). Each pattern offers distinct advantages and challenges in terms of stability, energy capture, and system complexity.

Licitra et al. (2019) conducted an in-depth performance assessment of a small-scale low-mass fixed-wing AWE system in pumping mode using an optimal control framework. Their findings challenge the common debate on the superiority of lemniscate versus circular trajectories by showing that, under equal boundary conditions, both patterns yield comparable power output. The study further emphasises that practical considerations, such as flight area requirements and mechanical stress, may ultimately drive the choice of flight pattern rather than efficiency alone. This work expands on their conclusions using a much heavier and larger kite, a detailed controller environment and a user-friendly simulation framework for open-source collaborations.

Specifically, this study focuses on the development of a basic flight controller for a fixed-wing AWE system, designed in a Matlab® Simulink® environment, with the purpose of comparing different flight patterns flown by heavy kites. The controller is engineered to replicate the entire pumping cycle of a ground-generation kite system, simulating the critical phases of power generation (traction) and its recovery (retraction). By modelling the kite's flight path and control dynamics within this virtual environment, the model can provide valuable insights into the performance and efficiency of different flight strategies.

Control and navigation of AWE systems often follow a hierarchical control structure, as commonly proposed for ground-generation rigid-wing systems (Rapp et al., 2019; Vermillion et al., 2021). This cascaded approach effectively breaks down the complex control problem into manageable sub-problems, allowing for optimal customisation of each control layer. The higher-level control is typically managed by a finite state machine, which supervises transitions across various flight operations, including launch, traction, retraction, and safety manoeuvres.



**Figure 1.** Control architecture representation, featuring outer and inner control loops, for a ground-generation AWE system.

For path following, target points are frequently utilised to guide the kite closely along predefined trajectories or to give a more loose guidance approach with a planned path. In van der Vlugt et al. (2013), four waypoints were used to steer a soft-kite in stable figure-of-eight downloop manoeuvres. Erhard and Strauch (2013); Fagiano et al. (2014) demonstrate the feasibility of achieving periodic figure-of-eight flight paths by alternating between two target points, also known as the bang-bang control theory used in practice by Skysails at the time. Fechner and Schmehl (2016) added a geometric construction of the planned

50 pumping cycle flight path to the four waypoints controller of van der Vlugt et al. (2013). Although these methods result in flying less defined path shapes, making it harder to quantify controller performance, their simplicity and computational efficiency make them appealing for real-world applications and sometimes even more superior in power production.

Another method is continuous path parametrisation, where the entire path is discretised in points which are tracked by the navigation system. A widely studied controller logic using this method is given by the  $L_1$  guidance logic. It calculates  
55 the required centripetal acceleration to define a reference roll angle, facilitating precise path following and enhanced system performance. This logic was initially proposed by Park et al. (2004) and later refined by Fernandes et al. (2022) to the so-called  $L_0$  guidance logic. Both methods are a widely adopted non-linear path following strategy in aerial vehicle navigation. Fernandes et al. (2022) also shows that the  $L_0$  guidance logic ensures asymptotic stability and is particularly well-suited for AWE systems.

60 Additionally, controlling the kite's attitude and dynamics is critical in ensuring stable and efficient AWE system operation. For flexible membrane wings, the turn rate law proposed by Erhard and Strauch (2013) links kite steering inputs to its course rate. However, this law does not apply to fixed-wing systems, where dynamic forces and moments are much more prominent.

An example of a more advanced control strategy can be seen in the flight controller presented by Ruiterkamp and Sieberling (2013), where the longitudinal and lateral motions of the kite are decoupled and controlled independently. This approach  
65 involves breaking down the figure-of-eight curve into discrete target points and using linear controllers to convert these into reference roll angles. However, challenges remain, particularly in maintaining the tether tension within safe limits.

Other advanced control strategies, which include the use of continuous path parameterisation, exist too. Jehle and Schmehl (2014) employ a cascaded controller using feedback linearization of an empirical steering-to-yaw rate model combined with a non-linear tracking law on the unit sphere to align the kite's flight path with a prescribed trajectory. Rapp et al. (2019) combine  
70 a PID controller for state-ideal path error correction with non-linear dynamic inversion to achieve the desired kite attitude. Lyapunov-based controllers, as developed by Li et al. (2015), focus on controlling kite attitude and rate error dynamics through differential and proportional control laws, addressing both translational and rotational motions independently.

The MegAWES 3 MW fixed-wing reference kite (Eijkelhof and Schmehl, 2022) is used in conjunction with the new improved flight controller developed by Rossi (2023). The earlier implemented controller proposed by Eijkelhof and Schmehl  
75 (2022) is complex and requires many controller parameters to be tuned for an optimal trajectory. This makes the controller not suited for a comprehensive study of the flight pattern. Therefore, a simpler, easier-to-tune controller is desired.

The main objective of the present work is the development of a simulation framework that allows comparing different flight patterns using the same operational environment, kite design and flight controller. The path planning is based on the described  $L_0$  logic (Fernandes et al., 2022), and the attitude control of the kite consists of a cascaded PID control loop based on Eijkelhof  
80 (2019). To have a consistent system for the analysis of the flight paths, the MegAWES reference kite described by Eijkelhof and Schmehl (2022) is used. A new winch design and controller are implemented as developed in Hummel et al. (2024b). The winch has been better sized for the system size of the MegAWES reference kite, and the winch controller has been changed to follow a power-optimal strategy.

The remainder of the paper is organised as follows. In Section 2, we will provide a comprehensive overview of the numerical framework and describe the design and implementation of the flight controller in Matlab<sup>®</sup> Simulink<sup>®</sup>, introduce the winch controller, present the strategy for obtaining comparative flight paths and present the reference system. In Section 3, a detailed analysis of the simulation results comparing the circular and two figure-of-eight flight paths is presented. Finally, in Section 4, a conclusion is drawn based on the results.

## 2 Methodology

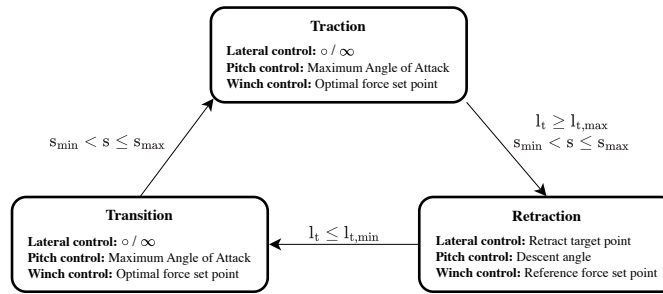
In this section, the numerical framework is described, which is used to compare the three different flight paths. First, the flight controller is discussed, split up into lateral and longitudinal control and the reference systems. Second, the reference kite model and winch are discussed.

### 2.1 Flight controller

The development of the flight control system for the fixed-wing AWE system is crucial for ensuring reliable and efficient operation. This system is designed to handle the intricate dynamics of tethered flight, which involves managing both the kites lateral and longitudinal motions. The control architecture is based on a cascaded control approach, which separates the control tasks into more manageable sub-problems, allowing for precise tuning and optimisation of each component. This section outlines the reference systems used to model the kites flight dynamics, the methodologies employed in designing the state machine for switching between phases, as well as the lateral and longitudinal control systems of the kite.

Figure 2 illustrates the control state machine structure designed for the system, detailing the transitions and control objectives for each flight phase. This state machine framework enables smooth transitions between traction, retraction, and other phases, optimising power output and stability under varying operational conditions.

In the traction phase, lateral and pitch control are focused on maintaining the maximum angle of attack for optimal energy capture, while winch control enforces an optimal force set point to manage tether tension. The transition phase from retraction to traction adjusts lateral and pitch controls similarly to the traction phase, driving the angle of attack to its peak to ensure longitudinal stability until the kite reaches the designated pattern target point to go back into traction. During the retraction phase, lateral control reorients to a pre-determined retraction target point, pitch control tracks a descent angle, and winch control reduces the tether tension to a reference force set point, effectively preparing the system for the next cycle.



**Figure 2.** The control state machine describing the transitions and control objectives for each flight phase. The triggers to switch between phases are shown next to the arrows, where  $l_t$  is the tether length and  $s$  is the dimensionless path variable resembling the position along the pattern.

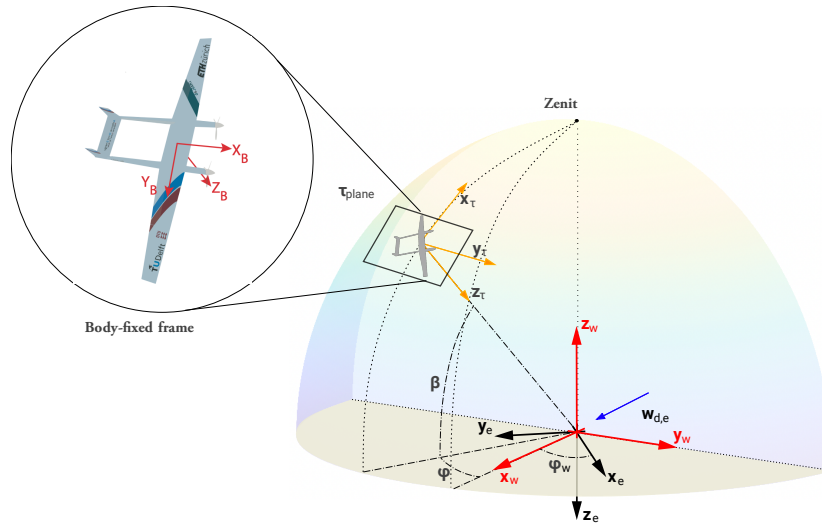
### 2.1.1 Coordinate frames

110 Various coordinate frames are used to model the entire system and effectively represent the many vector quantities that are involved. In most cases, these coordinate frames align with those commonly used in the flight mechanics literature, but some others are specially introduced for the AWE domain. This section presents a description and graphical representation of the reference frames used throughout this study.

Figure 3 presents the inertial(e), wind(w), body(B) and tangential plane( $\tau$ ) reference frames. In this work, the wind direction is aligned with the inertial x-axis ( $\varphi_w = 0$ ). Because the wind reference frame has the x-axis aligned with the wind direction, both inertial and wind x-axes coincide. The inertial reference frame is defined as a North-East-Down (NED) coordinate system with the ground station placed in the origin and the z-axis pointing into the ground. This definition is consistent with the standard approach in aerospace literature and is also implemented in the internal aerospace Simulink block.

To guide the kite through the wind window and to define the desired flight path for the traction phase, it is convenient to define a reference frame centred in the kite's centre of gravity (i.e. kite position) and tangential to the flight sphere. This frame, shown in Figure 3, can be obtained through a sequence of transformation matrices starting from the wind coordinate system.

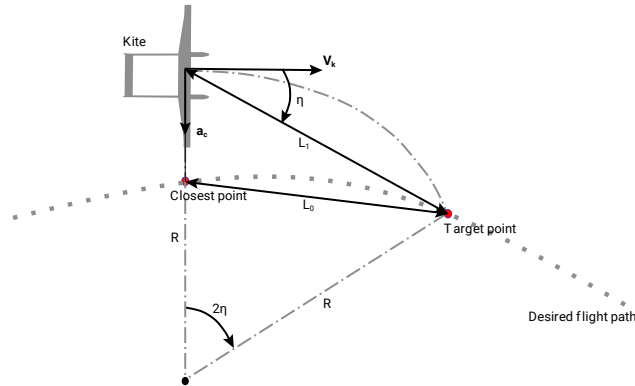
The body coordinate system is fixed according to the position and orientation of the kite. In this study, the kite is considered rigid, and any real-time deflection or deformation is not taken into account.



**Figure 3.** Inertial (e), wind (w), body (B) and tangent plane ( $\tau$ ) reference systems. Visualisation of azimuthal ( $\varphi$ ) and elevation ( $\beta$ ) angle along with wind direction ( $\varphi_w$ ).

### 2.1.2 Lateral control

125 The lateral controller requires a controller objective. This objective is determined by the path following module. This work utilises an adapted version of the  $L_1$  controller logic, a discretised  $L_0$  controller logic. As both methods are similar in principle, the  $L_1$  method is described first, from which the  $L_0$  method is then derived. The concept is visualised in Figure 4.



**Figure 4.** Principle of  $L_1$  and  $L_0$  guidance logic. The closest point to the kite and the target point are highlighted in red.  $V_k$  is the kite velocity magnitude,  $a_c$  the required acceleration and  $\eta$  the heading.

The  $L_1$  controller logic is typically a control strategy used in guidance systems in flight controllers for path following, where a dynamical system must track a desired trajectory. The key principle behind the  $L_1$  logic is that it defines a distance metric,

130 often referred to as the  $L_1$  distance, which measures the separation between the actual position of the system (e.g. kite or aircraft) and a designated target point on the intended path. This distance is often used as a control parameter to ensure that the system moves toward the desired trajectory by looking either closer or further ahead to determine an optimal target position to track. The  $L_1$  controller has only one adjustable design parameter, the  $L_1$  distance, which can be tuned to achieve faster or smoother convergence to the desired path. This makes the strategy simple to tune and ideal in the context of this work. Park et al. (2004) demonstrates the effectiveness of this tracking method and explains how to optimise the parameter across different scenarios, including straight lines, perturbed paths, and circular trajectories. The approach guarantees asymptotic stability, as shown by a Lyapunov invariant set theorem analysis. This makes the  $L_1$  control strategy particularly well-suited for non-linear systems, offering an advantage over traditional linear control methods.

140 Rather than specifying the  $L_1$  distance as a control metric, a discretised interpretation of the  $L_0$  distance is used (Fernandes et al., 2022). In this approach, the distance to the target point is calculated from the nearest point along the trajectory projected from the kites position.

In contrast to conventional methods, this formulation broadens the field of attraction toward the desired course, guaranteeing that the guidance system consistently retains a target point on the path, even when the kite drifts further from the desired trajectory. When the  $L_1$  distance is used, the controller becomes confused when the kite is further away from the trajectory than the specified  $L_1$  distance. There are several ways to solve this, for example, by widening the distance when it cannot converge on a point on the trajectory. However, using the  $L_0$  distance instead deemed to be the most effective.

150 Due to the closed and intersecting geometry of certain flight paths, accurately selecting the target point becomes more complex. When dealing with a continuous curve, iterative techniques, such as Newton-Euler methods, are typically employed to determine both the nearest and target points with a manageable number of iterations. However, for the discrete representation of the path as a finite set of points, an alternative approach is necessary.

In the studied scenario, the set of path points is discretised using the dimensionless path variable  $s$  over the interval from 0 to  $2\pi$ . This ensures unique tracking points, independent of path shape. The path is discretised on the tangent plane and then projected onto a spherical surface. Using a path parametrisation dependent on this variable  $s$ , Cartesian path coordinates can be calculated and stored.

155 The discretisation of the circular path is straightforward given the definition of a circle. The figure-of-eight can be defined in several different ways, a Lissajous or (hyperbolic) lemniscate of Booth, for example. Lissajous figures are looping patterns formed by the combination of two perpendicular harmonic oscillations. By choosing the right parameters a shape similar to a figure of eight can be obtained. The lemniscate of Booth is a generalised version of the lemniscate of Bernoulli, which was first introduced by the brothers Bernoulli in 1694. Bernoulli's lemniscate was then generalised in the 19th century by James Booth. 160 The lemniscate of Booth can be described as the set of points where the product of distances to two foci of the hyperbolic function is constant. When the hyperbolic function is rectangular, the lemniscate of Bernoulli is obtained Gray (1997). The lemniscate of Booth is used in this framework and given the path variable  $s$ , the shape is defined in the tangent plane by the

following coordinate expressions and then projected on the flight sphere.

$$x_{\text{fig8}}(s) = \frac{b_{\text{Booth}} \sin s}{1 + \left(\frac{a_{\text{Booth}}}{b_{\text{Booth}}}\right)^2 \cos^2 s}, \quad (1)$$

$$165 \quad y_{\text{fig8}}(s) = \frac{a_{\text{Booth}} \sin s \cos s}{1 + \left(\frac{a_{\text{Booth}}}{b_{\text{Booth}}}\right)^2 \cos^2 s}, \quad (2)$$

where  $a_{\text{Booth}}$  and  $b_{\text{Booth}}$  define the height and width of the figure of eight, respectively. For this study, a discretisation of 50 points was chosen. This leads to a smooth path discretisation but is still computationally efficient.

Additionally, a distance array is introduced, containing the distances between the kites current position and each point on the path. This array is organised cyclically, allowing the algorithm to continually search for the closest point as the kite follows the closed-loop trajectory. To select the correct nearest point, special attention is needed for complex paths like the figure-of-eight. In this shape, the kite crosses over multiple intersections, which can lead to wrong tracking points. To overcome this problem, the selection process uses a smaller subset of the distance array, starting from the previous time step. This proved to be a reliable method to choose the correct projected kite location on the trajectory.

175 Instead of choosing a distance value as the controller parameter, the tracking point is determined using a set number of elements ahead. After identifying the closest point, the target point is set as the  $n^{\text{th}}$  element ahead in the sequence. This guarantees that the target point remains consistently defined as  $n$  points ahead of the nearest one, where  $n$  serves as a tunable discrete control parameter.

The lateral controller determines the actuator demands based on the tracking point given by the path following module. The target vector is computed using the coordinates of both the kite and the target point, within the wind reference frame described in Section 2.1.1. Using the appropriate transformation matrices, the target vector and the kites velocity are projected onto the tangent plane. This tangent plane is visible in Figure 3 and is tangent to the sphere surface, with a radius equal to the straight tether length and the centre at the ground station.

The resulting projections are then used to derive the heading angle  $\eta$ . To avoid impractically sharp turns, which could lead to hazardous manoeuvres, the calculated heading angle  $\eta$  is restricted to  $\pm \frac{\pi}{4}$ . Finally, by considering all forces acting on the kite, the desired roll angle  $\phi_{\tau, \text{des}}$ , relative to the tangent plane, is determined as

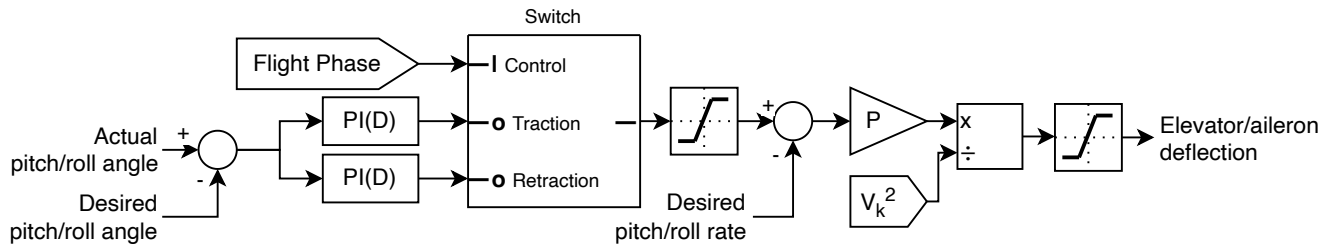
$$\phi_{\tau, \text{des}} = \arcsin \left( \frac{a_c m + F_{g,y} \cos \phi_{\tau, \text{act}} + F_{g,z} \sin \phi_{\tau, \text{act}}}{F_L} \right), \quad (3)$$

where  $m$  is the kite mass,  $F_g$  is the gravitational force acting on the kite,  $\phi_{\tau, \text{act}}$  is the actual roll angle,  $F_L$  is the lift force and  $a_c$  is the lateral acceleration needed for the vehicle to trace a curved trajectory. This acceleration can be calculated as

$$a_c = 2 \frac{V_k^2}{L_1} \sin \eta, \quad (4)$$

190 where  $V_k$  is the kite velocity magnitude, and  $\eta$  is the angle between the kite velocity and the direction to the reference point.

This desired roll angle is then converted into a demand for the aileron deflection using multiple PI controllers, illustrated in Figure 5.



**Figure 5.** Flow diagram of the attitude and rate controller for both lateral and longitudinal control. The lateral controller needs a PID to accurately follow the desired input, and for the longitudinal controller, a PI controller suffices. The gains are tuned separately for traction and retraction. The integral part of the PI(D) controller is reset at the start of the specific flight phase to prevent windup.

### 2.1.3 Longitudinal control

One of the key factors influencing power extraction from the wind during crosswind flight of AWE systems is the tether force, which is directly linked to the kites lift. To maintain proper tether tension, the kites angle of attack must be controlled via the longitudinal or pitch controller.

Since the systems primary goal is to maximise wind energy extraction, the control of longitudinal flight dynamics aims to sustain a high  $C_L^3/C_D^2$  ratio to optimise power generation. Loyd (1980) showed that the maximum theoretical power extraction is proportional to this ratio. Considering tether drag, the highest feasible ratio is practically lower than for untethered aircraft. Hence, it is essential to consider the total systems combined  $C_L^3/C_D^2$  ratio, including the kite and tether drag. In general, a higher  $C_L^3/C_D^2$  ratio corresponds to a higher angle of attack when including the tether drag, yielding more power. Hence, a simple approach is used, choosing a constant high angle of attack as a reference target during the power production phase.

As developing a new reference kite and aerodynamic model is beyond the scope of this paper, the existing aerodynamic data of the MegAWES kite is used (Eijkelhof and Schmehl, 2022). Using this, a target angle of attack of approximately  $4^\circ$  was chosen for the traction phase to keep the kite operating within the linear region. This corresponds to an approximate  $C_L$  of 1.8. Hence, the stall region is entirely avoided. While possible in numerical studies to neglect tether force control, in practical applications, it is critical to ensure that tether tension does not exceed its limits. During winch controller saturation, it may require changing the desired angle of attack to lower the aerodynamic performance as done in Hummel et al. (2024a). This work does not include such a tether force controller, but the limit is taken into account in the optimisation objective.

The desired angle of attack  $\alpha_{des}$  is then used as an objective for the pitch controller, which adjusts the kite's pitch by means of elevator deflection  $\delta_e$ . This conversion is done by the PI cascaded loops visible in Figure 5.

While following circular or figure-eight paths, the longitudinal controller must compensate for external disturbances, including winch and tether forces and kite dynamics. Wind plays a significant role, particularly as the relative wind direction changes during ascent and descent. When the kite flies against the wind, the relative wind speed increases, raising  $\alpha_a$ , while descending

215 in the same direction as the wind decreases  $\alpha_a$ . These oscillations, dependent on the velocity along the path, must be actively managed.

## 2.2 Winch controller

The winch, which includes the drum, drivetrain, and generator, is modelled as a single rotating body with inertia  $J$  and a constant radius  $R$  (Hummel et al., 2024b) positioned in the origin of the wind and inertial reference frames. The modelling approach simplifies the equations by ignoring viscous friction, as the friction torque is much smaller than the forces exerted by the tether on the winch and the control motor torque. Additionally, the radius is assumed constant, despite the spooling of the tether, because the changes in radius are small and slow, making their dynamic impact negligible. Two primary moments act on the winch: the tether force multiplied by the winch radius and the motor torque, both of which are used in the control strategy.

225 An optimal control curve is derived to define a control target. The ground tether force, the force at the winch, is calculated using a quasi-steady model, neglecting cosine losses and the kites mass (Schmehl et al., 2013)

$$F_t = C v_{a,r}^2, \quad (5)$$

where

$$C = \frac{1}{2} \rho S C_L E_{eq}^2 \left( 1 + \frac{1}{E_{eq}} \right)^{\frac{3}{2}}, \quad (6)$$

230 where  $F_t$  is the ground tether force,  $v_{a,r}$  the radial component of the apparent wind velocity,  $\rho$  the air density,  $S$  the reference wing area,  $C_L$  the lift coefficient,  $E_{eq}$  the equivalent lift-to-drag ratio (including tether drag).

Instead of modelling individual forces like gravity or wind speed variation, an equivalent wind speed is used to account for these effects. Choosing an optimal reel-out factor  $f^*$ , to be 1/3 (Loyd, 1980), the motor torque on the winch aims to balance out the torque from the tether force at steady-state. The reel-out factor is defined as reeling velocity divided by the wind speed. This results in a winch control curve, often called the optimal force-squared speed manifold, where the motor torque  $T_m$  is the product of the optimal tether force and winch radius

$$T_m = 4C v_t^2 R, \quad (7)$$

where  $v_t$  is the tether reeling speed.

In Hummel et al. (2024b), the winch is sized for the MegAWES kite as shown in Table 2. The given size parameters ensure a robust and steady response of the winch when trying to stay on the optimal control curve defined by Equations (5) to (7).

## 2.3 Comparative flight path strategy

To support the comparative analysis of circular and figure-of-eight flight patterns, this study employs the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) Hansen (2006). The CMA-ES method iteratively refines parameters by minimising a specified objective function, allowing for targeted adjustments in both controller settings and flight path characteristics.

245 Rather than aiming for a global optimum, the optimisation serves as a strategic exploration of the design space, focusing on  
 identifying representative configurations for each flight pattern. This sub-optimisation approach thus provides a balanced set of  
 configurations that enable a fair and insightful comparison of the performance, stability, and structural implications of different  
 flight patterns, aligning directly with the study's goal of understanding each pattern's relative advantages and limitations. This  
 means the solution should be in no way interpreted as an optimal condition. This method works well for different kite designs  
 250 and scales where the initial condition is hard and time-consuming to determine. The numerical exploration using CMA-ES  
 allows for finding a parameter set which converges, which is key to proceeding with any optimisation process. Gradient-based  
 optimisation methods would work great to obtain an optimised result once such an initial condition is known, yet, even though  
 there are methods to lower the chance, one will never know for certain if they arrive at a local or global minimum. These  
 methods are considered better-suited for a more detailed analysis of a single pattern.

255 Table 1 provides a set of system parameters which could be varied by the optimiser. Equation (8) shows the constrained  
 single-objective used. The main objective is to maximise the average cycle power ( $\text{mean}(P_{\text{mech}})$ ). The applied penalties are  
 based on exceeded maxima, which are carefully selected to constrain the design space. The penalties are applied only when  
 maxima are exceeded. The weights were chosen based on importance. The cross-track error, the error on position with respect  
 to the planned trajectory, is considered less important than velocity, tether force and peak-to-average-power ratio. Eventually,  
 260 the final comparison is only considering solutions where the maxima are never exceeded, effectively constraining the design  
 space. Only the peak-to-average-power ratio (PAPR) never goes below its limit. This does, therefore, influence the optimiser  
 result, but as it is the only non-zero penalty, it does make the algorithm look for solutions with a PAPR as close to 2.5 as  
 possible, which is in this study considered a desired outcome.

$$C_{\text{obj}} = -\text{mean}(P_{\text{mech}}) + p_{\text{cte}} + p_{V_k} + p_{F_t} + p_{\text{papr}}, \quad (8)$$

265 with constraints

$$p_{\text{cte}} = \begin{cases} 10^2 \cdot \left( \frac{\max(\text{cross-track error})}{75\text{m}} - 1 \right), & \text{if } \max(\text{cross-track error}) > 75 \text{ m} \\ 0, & \text{otherwise} \end{cases}$$

$$p_{V_k} = \begin{cases} 10^4 \cdot \left( \frac{\max(V_k)}{100 \text{ ms}^{-1}} - 1 \right), & \text{if } \max(V_k) > 100 \text{ ms}^{-1} \\ 0, & \text{otherwise} \end{cases}$$

$$p_{F_t} = \begin{cases} 10^4 \cdot \left( \frac{\max(F_t)}{1664910 \text{ N}} - 1 \right), & \text{if } \max(F_t) > 1664910 \text{ N} \\ 0, & \text{otherwise} \end{cases}$$

$$p_{\text{papr}} = \begin{cases} 10^5 \cdot \left( \frac{\max(\text{PAPR})}{2.5} - 1 \right), & \text{if } \max(\text{PAPR}) > 2.5 \\ 0, & \text{otherwise} \end{cases}$$

**Table 1.** Operational and controller parameters varied during optimisations.  $K_p$ ,  $K_i$  and  $K_d$  are the PID gains, respectively.

Controller	Flight path	Tether
$K_p$ , $K_i$ winch (retraction)	Figs $a_{\text{Booth}}$ *	Tether length max.
$K_p$ roll rate (traction)	Figs $b_{\text{Booth}}$ *	Tether length min.
$K_p$ roll rate (retraction)	Circle radius*	Retraction force
$K_p$ pitch rate (traction)	Elevation angle	
$K_p$ pitch rate (retraction)		
$K_p$ , $K_i$ , $K_d$ roll (traction)		
$K_p$ , $K_i$ , $K_d$ roll (retraction)		
$K_p$ , $K_i$ pitch (traction)		
$K_p$ , $K_i$ pitch (retraction)		

\* Whether the parameter is needed depends on the chosen flight path.

## 2.4 Additional system parameters

As this work focuses on comparing flight paths, it is of key importance to keep as many factors as possible the same throughout the analysis. Therefore, for each case study, the same kite, ground station, and tether are used. Similarly, one wind shear model without turbulence is chosen and kept constant throughout the analysis. The wind shear is determined from the averaged Ijmuiden measurement data presented in Schelbergen et al. (2020). The 3 MW MegAWES kite is chosen as the ground-generation fixed-wing kite (Eijkelhof and Schmehl, 2022). Since the original MegAWES simulation framework used a winch which was not sized for the megawatt-scale power, a better-sized winch is used instead (Hummel et al., 2024b).

The kite is modelled as a rigid body (six degrees of freedom). The total sum of forces acting on the kite is composed of the aerodynamic force, the tether force and the gravitational force. The aerodynamic force is a resultant force combining both lift, drag and side force.

The tether is modelled similarly to the original MegAWES simulation environment. The tether is modelled as quasi-steady, discretised by lumped masses which are connected by straight elements and have a stiffness based on the Dyneema® material.

Table 2 shows a summary of the specifications of the entire system. This includes kite design, winch size and tether specifications.

## 2.5 Comparison criteria

To evaluate the flight patterns, the following key criteria are investigated: cycle-averaged power, power oscillations (power quality) and projected ground area.

Cycle power is the average power output over a complete pumping cycle. It serves as a primary measure of system efficiency, representing the overall energy production capability of the system. Higher cycle-averaged power indicates more efficient wind energy extraction. The cycle power can be calculated using only the numerator of Equation (10).

**Table 2.** General planform parameters of the wing, tail and fuselage and characteristics of the winch and tether, adapted from (Eijkelhof and Schmehl, 2022).

Parameter	Value	Unit
Inertia $J_{xx}$	$5.7680 \times 10^5$	$\text{kg m}^2$
Inertia $J_{yy}$	$0.8107 \times 10^5$	$\text{kg m}^2$
Inertia $J_{zz}$	$6.5002 \times 10^5$	$\text{kg m}^2$
Mass	$6.8852 \times 10^3$	kg
<i>Wing / RevE<sub>H</sub>C airfoil</i>		
Span	42.47	m
Chord <sub>root</sub>	4.46	m
Chord <sub>tip</sub>	2.11	m
LE sweep	2	°
Aspect ratio	12.0	-
Surface area	150.45	$\text{m}^2$
Twist <sub>root→tip</sub>	5 → 0	°
<i>Horizontal tail / NACA0012 airfoil</i>		
Span	7.6	m
Chord	2.8	m
<i>Vertical tail / NACA0012 airfoil</i>		
Span	3	m
Chord	2.8	m
<i>Winch</i>		
Total inertia	$1.0 \times 10^4$	m
Radius	1.5	m
<i>Tether / Dyneema ®</i>		
Density	$0.97 \times 10^3$	$\text{kg m}^{-3}$
Modulus	$1.16 \times 10^{11}$	Pa
Ultimate strength	$3.6 \times 10^9$	Pa
Cylindrical $C_D$	1.2	-

Power oscillations (power quality) reflect the stability and consistency of power generation. A system with lower power oscillations provides more stable power output, which is crucial for integration into the electrical grid. Hence, minimising power fluctuations is a desirable characteristic in AWE systems. The power quality is quantified using the Peak-to-Average Power Ratio (PAPR) during the traction phase. It is defined as the ratio between the maximum instantaneous mechanical power

and the average power over the traction interval:

$$\text{PAPR} = \frac{\max_{t \in T_{\text{traction}}} P_{\text{mech}}(t)}{\frac{1}{T_{\text{traction}}} \int_{T_{\text{traction}}} P_{\text{mech}}(t) dt} \quad (9)$$

where  $P_{\text{mech}}(t)$  is the instantaneous power at time  $t$ , and  $T_{\text{traction}}$  denotes the time interval corresponding to the traction phase.

The projected ground area provides an estimate of the space required for each system when deployed in a farm configuration. It is crucial to determine how dense systems can be arranged within a given surface area, directly influencing the potential energy density of the farm. Additionally, it offers a preliminary assessment of the necessary safety buffers, which are vital for mitigating the risk of system interference and ensuring operational safety. The projected ground area is defined as the area of the two-dimensional projection of the flight trajectory onto the ground plane. Additionally, the surface area power density is used to evaluate the average power output normalised by the projected ground area:

$$P_d = \frac{\frac{1}{T_{\text{cycle}}} \int_{T_{\text{cycle}}} P_{\text{mech}}(t) dt}{\text{PGA}} \quad (10)$$

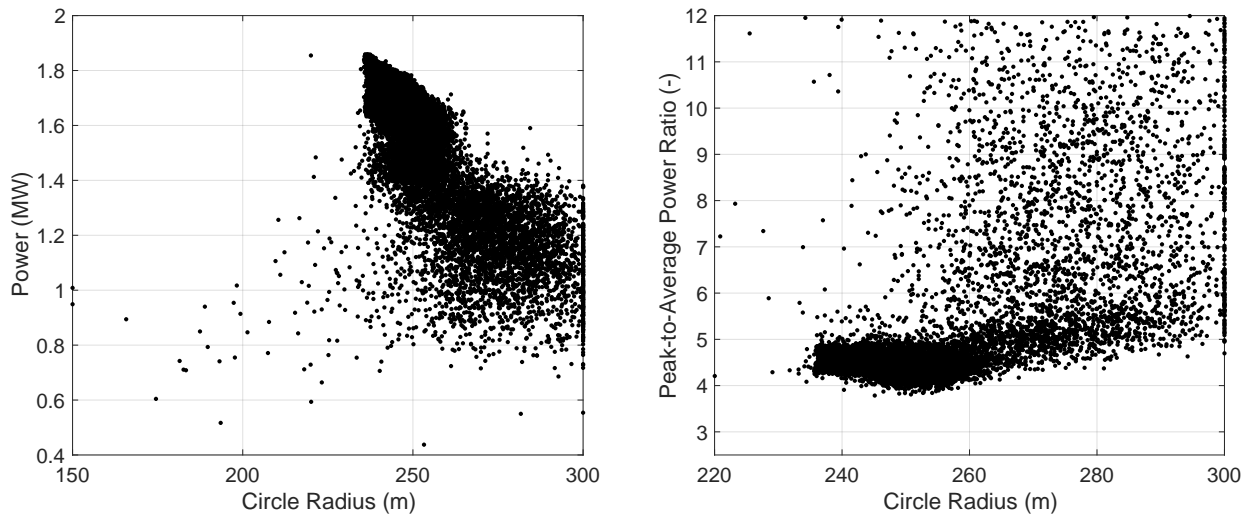
where  $P_d$  is the surface area power density, PGA the projected ground area and  $T_{\text{cycle}}$  denotes the time interval corresponding to the entire pumping phase.

### 3 Results

This section presents a detailed comparison of the circular and figure-of-eight flight patterns, evaluating their performance based on key metrics such as cycle power and peak-to-average power ratio. The simulations are performed in a consistent operational environment with a wind speed of 15 m/s across all tests. This wind speed is below the rated wind speed. Above the rated wind speed, a real-world kite system is limited to not exceed the rated power. This limit is not included in this simulation framework. Thus, a below-rated wind speed was chosen as a good compromise between high power output and a non-limited condition. First, the most optimal solution for a fair comparison is chosen. Second, the full pumping cycle is compared between patterns. Even though complete pumping cycles are compared, the focus has been on the traction phase, where the pattern makes a big difference, the retraction strategy is relatively similar in all cases and therefore discussed in less detail.

#### 3.1 Pattern exploration

In this section, only two of the earlier-mentioned three performance metrics are considered. The objective function focused on average cycle power, making it of key importance in selecting the cycle for detailed discussion in the next section. As the peak-to-average-power ratio (PAPR) constraint was not satisfied, this is included as well. First, the cycle power is compared to the circle radius in Figure 6. As the algorithm is free to choose any radius, many combinations of parameters are evaluated, hence multiple power results per radius. The optimal radius for this kite at the given wind speed, with the operation conditions explained throughout this paper, is around 220 m. This means that the diameter of the flight pattern is around 10.5 times the wingspan.

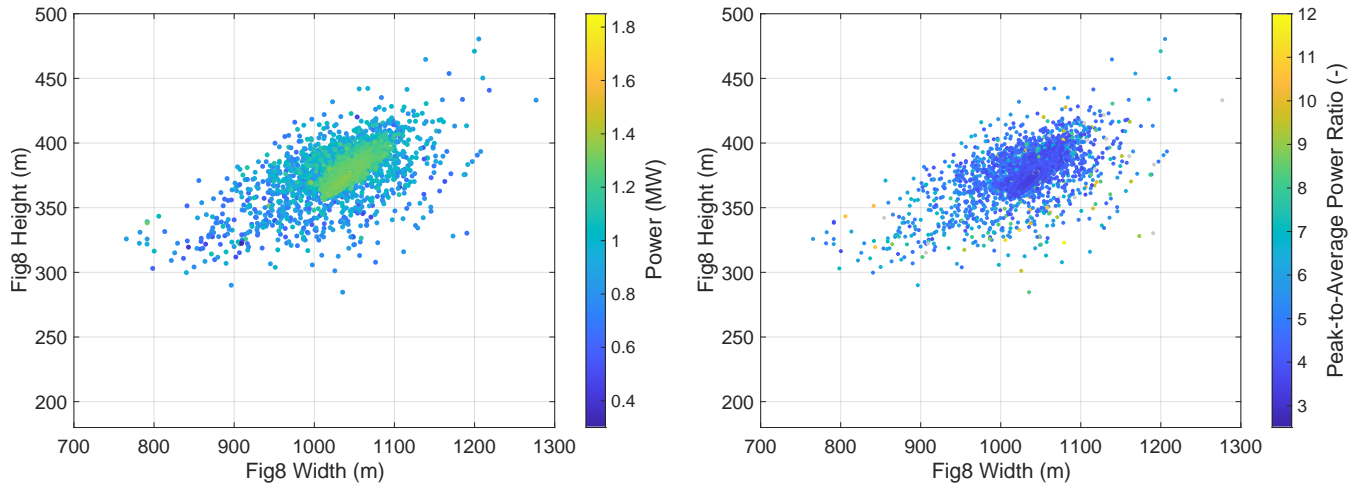


**Figure 6.** Circular pattern performance at 15 m/s wind speed with different circle radii. Left is the average cycle power. Right is the peak-to-average-power ratio.

From theory, a smaller radius would lead to a larger part of the path experiencing higher wind speeds, considering the cosine losses, and thus, one could expect a higher power extraction. However, there is a limit on how small the circle can be before other losses and constraints become dominant. One reason follows the results of the study performed by Makani, where smaller radii induce larger roll angles, negatively affecting the power production Tucker (2020). Another explanation is that smaller radii tend to cause higher tangential velocities, possibly exceeding the prescribed maximum velocity of  $100 \text{ ms}^{-1}$ . This follows from the definition of the centripetal force required to follow a curve. When the kite is already operating around its maximum aerodynamic capability, the optimiser looks for solutions with larger velocities to follow the sharper turns. If the maximum tangential velocity is exceeded, the optimisation objective is penalised, steering the optimiser to limit the maximum occurring velocity. Wake effects could further strengthen these findings as smaller radii would have a larger upwind wind speed reduction, but no wake model is included in the analysis and thus has no effect on the results. These reasons explain why there are a very limited number of data points at smaller radii.

Another important metric that needs to be considered is the PAPR. The peak power of the traction phase is divided by the average traction phase power. The large concentration of data points at low PAPR shows that the penalisation of the objective is working as expected. While optimising for more cycle power, the power peaks are minimised. In the given conditions, the most optimal PAPR is a little over 4. Even though some results show that it could obtain a slightly lower PAPR than 4, those solutions are deemed less optimal, with either lower average power or exceeding any of the other constraints. Accepting a lower cycle power would potentially lead to a lower PAPR. However, the same can be said for the other patterns, likely leading to similar differences.

A similar analysis is performed for both variations of the figure-of-eight. Figures 7 and 8 show the optimisation results, illustrating the geometry (width and height) of the figure-of-eight with respect to the cycle power on the left and the PAPR on the right.



**Figure 7.** Figure-of-eight down-loop pattern at 15 m/s wind speed with different pattern sizes at minimum tether length. Left is the average cycle power. Right is the peak-to-average-power ratio.

Both, down-loop and up-loop flight patterns converge to an optimal combination of width and height. The up-loop converges to smaller-sized figure-of-eights compared to the down-loop. This is the expected behaviour since especially the smaller-width figure-of-eight patterns remain more in the effective wind window. This benefits the upward flight.

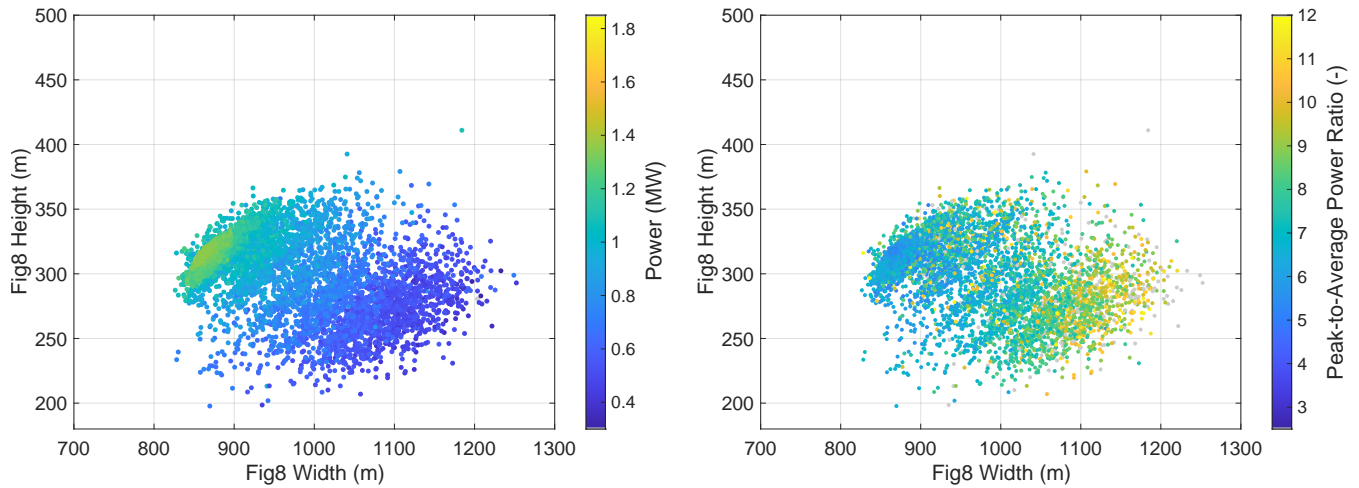
The right image in Figure 7 shows that the most optimal solution of the down-loop is limited at a lower cycle power than the circle pattern. The PAPR however, converges to the lower value of below 4. Similar to the circular pattern, lower PAPR solutions exist, but are less optimal.

The left image in Figure 8 shows that the most optimal solution of the up-loop is similarly limited at a lower cycle power than the circle pattern. Unlike the down-loop, the up-loop PAPR, however, converges to the highest PAPR value of the three patterns.

### 3.2 Pumping Cycle Comparison

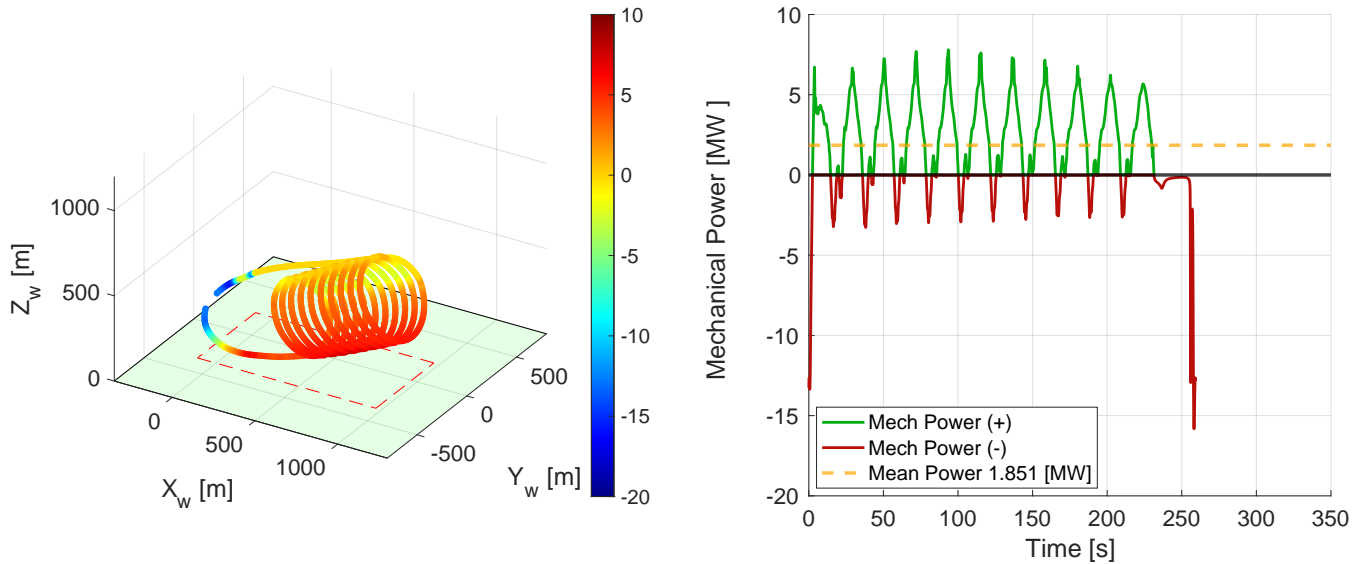
From the previous results, the most comparable path is selected for a more detailed comparison. Here, the flight patterns are compared based on the power oscillations (power quality), projected ground surface area and cycle average power.

Figure 9 shows the circular 3-dimensional flight path coloured by the mechanical power, which is shown with respect to time on the right. The projected ground area is shown in the red dashed box on the ground plane. The centerline of the cycle trajectory is slightly shifted on the y-axis, aligning the upward flight more with the centre of the wind window. As the target path is centred at zero azimuth, this result is solely a consequence of precise gain tuning and changing tracking accuracy along



**Figure 8.** Figure-of-eight up-loop pattern at 15 m/s wind speed with different pattern sizes at minimum tether length. Left is the average cycle power. Right is the peak-to-average-power ratio.

the pattern. Tracking accuracy can change as different velocities occur throughout the pattern, making it easier and harder to track a given target.



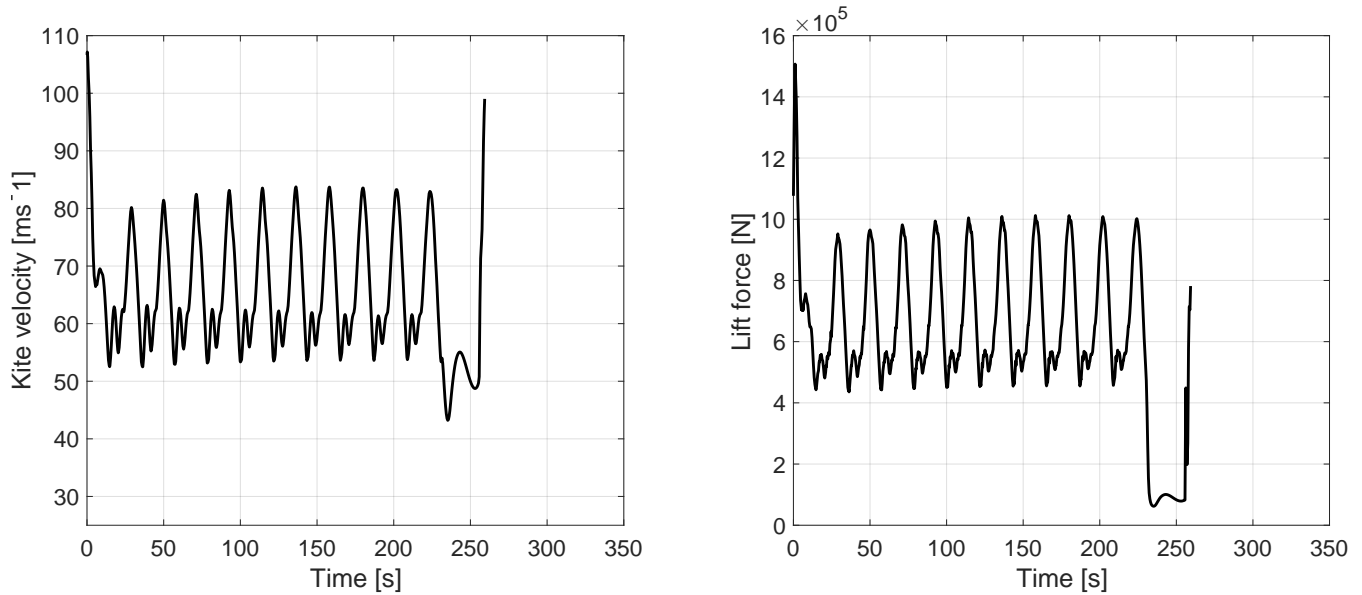
**Figure 9.** Circular flight path of the most optimised solution set, 15 m/s wind speed. Left is the 3D flight trajectory, which is coloured by mechanical power. Right is the mechanical power with respect to cycle time.

360 It can be noted that at this wind speed, most of the mechanical power is positive; however, during each loop, the winch needs to retract a bit to insert energy into the system to get it to the top of the circle. This extra required energy is due to the

gravitational losses, which the kite alone cannot compensate for. The cycle average is at 1.851 MW, which is much higher than the figure-of-eight flight patterns.

To illustrate the ground area that the system covers, the projected ground area is shown under the flight path. The converged circular trajectory under these conditions projected on the ground covers an area of 0.63 km<sup>2</sup> (0.58 km × 1.08 km). This results in a surface area power density of 2.94 MW km<sup>-2</sup>.

Figure 10 presents the velocity and lift force with respect to cycle time for the circle. As expected, the velocity and lift force more or less follow the same behaviour.

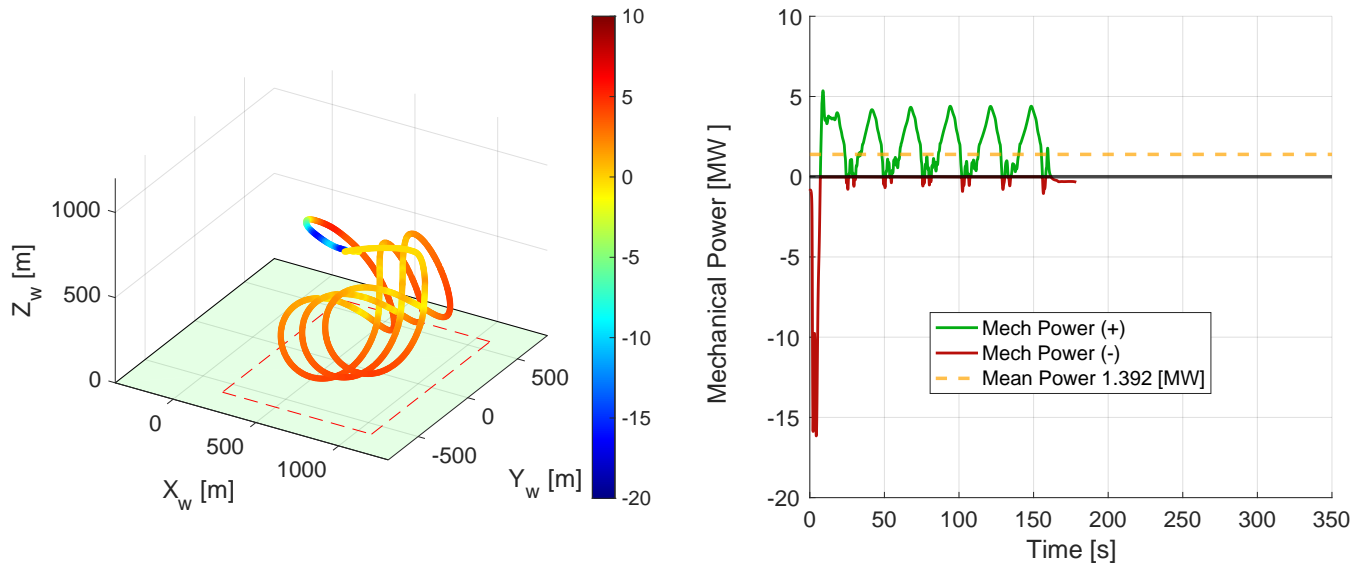


**Figure 10.** Circular flight path of the most optimised solution set, 15 m/s wind speed. Left is the kite velocity with respect to cycle time. Right is the lift force with respect to cycle time.

The maximum velocity is only exceeded at the start of the cycle. The relatively bad transition from retraction to the traction phase causes this spike in velocity and is, therefore, not considered a limiting factor in the validity of the result for this paper. Transition phases are highly complex and not relevant to the scope of this work. Higher velocity is reached at the end of the downward flight, slowing down on the way back to the upper part of the circle.

An additional performance metric that can be derived from these results is the dominant load frequency associated with the aerodynamic forces. Among these, the lift force emerges as the most significant. Specifically, when considering only the traction phase of operation, the lift force exhibits a cyclic load on the structure with a frequency of approximately 0.046 Hertz. In comparison to the down-loop phase, this higher cycle frequency, as well as a higher amplitude, suggests an increased likelihood of fatigue-related damage over time, as the system is subjected to more frequent load cycles.

Figure 11 shows the figure-of-eight down-loop 3-dimensional flight path coloured by the mechanical power, which is shown with respect to time on the right. The projected ground area is shown in the red dashed box on the ground plane.



**Figure 11.** Figure-of-eight down-loop flight path of the most optimised solution set, 15 m/s wind speed. Left is the 3D flight trajectory, which is coloured by mechanical power. Right is the mechanical power with respect to cycle time.

380 It can immediately be noted that at this wind speed, almost all of the mechanical power is positive. Out of the three patterns, this delivers a smoother power output, requiring less power smoothing equipment. At the centre of the figure-of-eight, the kite is right in the optimal part of the wind window. Using this part to fly up, the forces can use this beneficial wind to counteract gravity, reducing overall power oscillation. The cycle average is at 1.392 MW, which is lower than the circular path but slightly higher than the up-loop figure-of-eight.

385 The converged down-loop trajectory under these conditions projected on the ground covers an area of  $1.07 \text{ km}^2$  ( $1.19 \text{ km} \times 0.90 \text{ km}$ ). This results in a surface area power density of  $1.30 \text{ MW km}^{-2}$ .

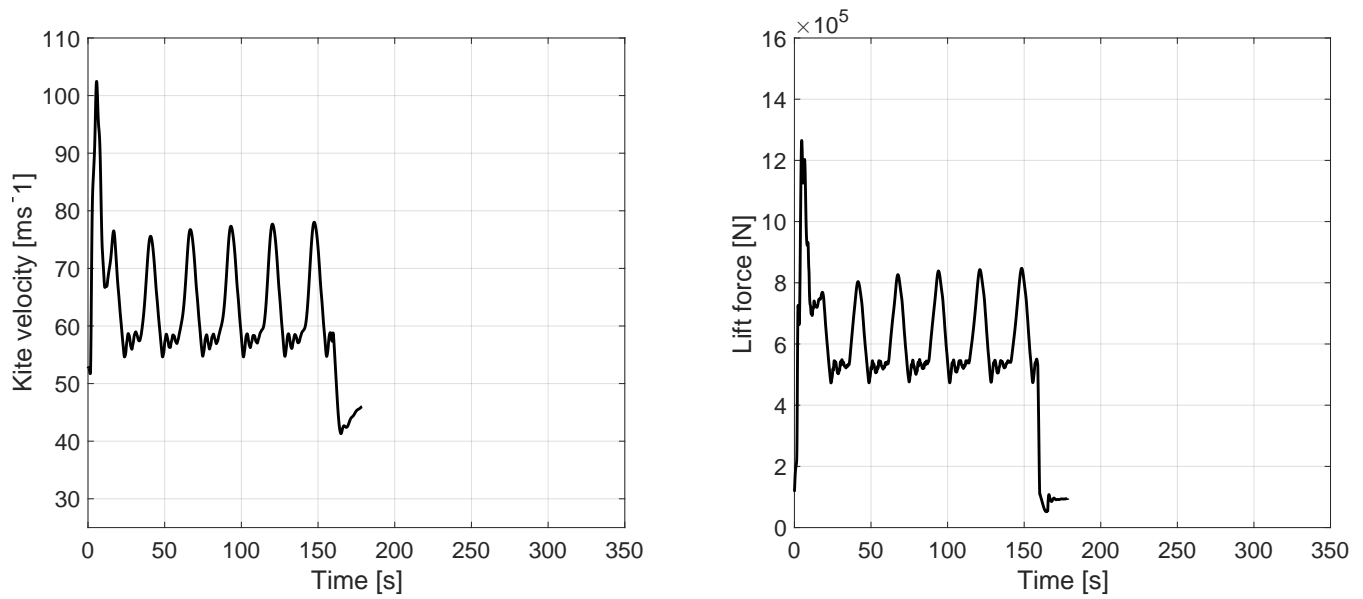
Figure 12 presents the velocity and lift force with respect to cycle time for the down-loop. Similarly to the circular path, the velocity and lift force follow the same behaviour.

The maximum velocity is slightly exceeded at the start of the cycle. As this is during the transition phase back into traction, 390 this is ignored. The higher velocity occurs during downward flight at the outer curves, while the kite slows down in the centre, flying up.

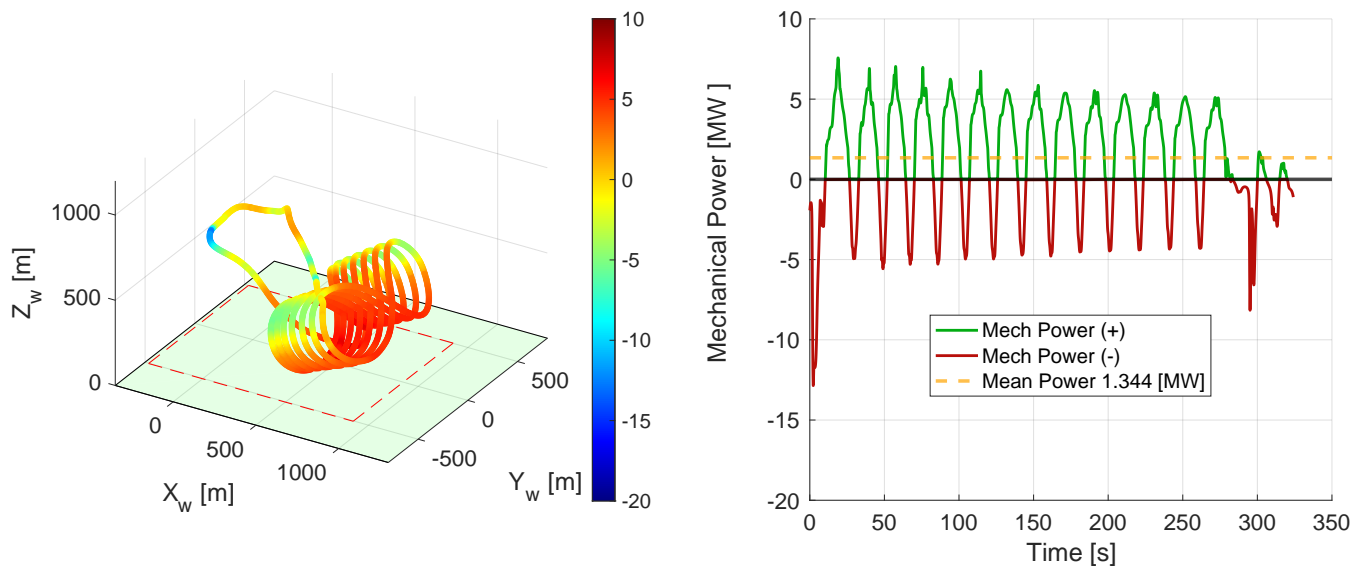
The right of Figure 12 shows that the dominant load frequency of the lift force is approximately 0.034 Hertz. Out of the three studied patterns, this is the lowest, having favourable effects on kite lifetime.

Figure 13 shows the figure-of-eight up-loop 3-dimensional flight path coloured by the mechanical power, which is shown 395 with respect to time on the right. The projected ground area is shown in the red dashed box on the ground plane.

It can be noted that at this wind speed, the mechanical power is the most oscillatory of all patterns, requiring more power smoothing than the others. Opposite to the down-loop, the gravitational force needs to be counteracted at the outer edges of the figure-of-eight, where the kite is at the least optimal part of the wind window. Using this part to fly up, the winch has to



**Figure 12.** Figure-of-eight down-loop flight path of the most optimised solution set, 15 m/s wind speed. Left is the kite velocity with respect to the cycle time. Right is the lift force with respect to cycle time.

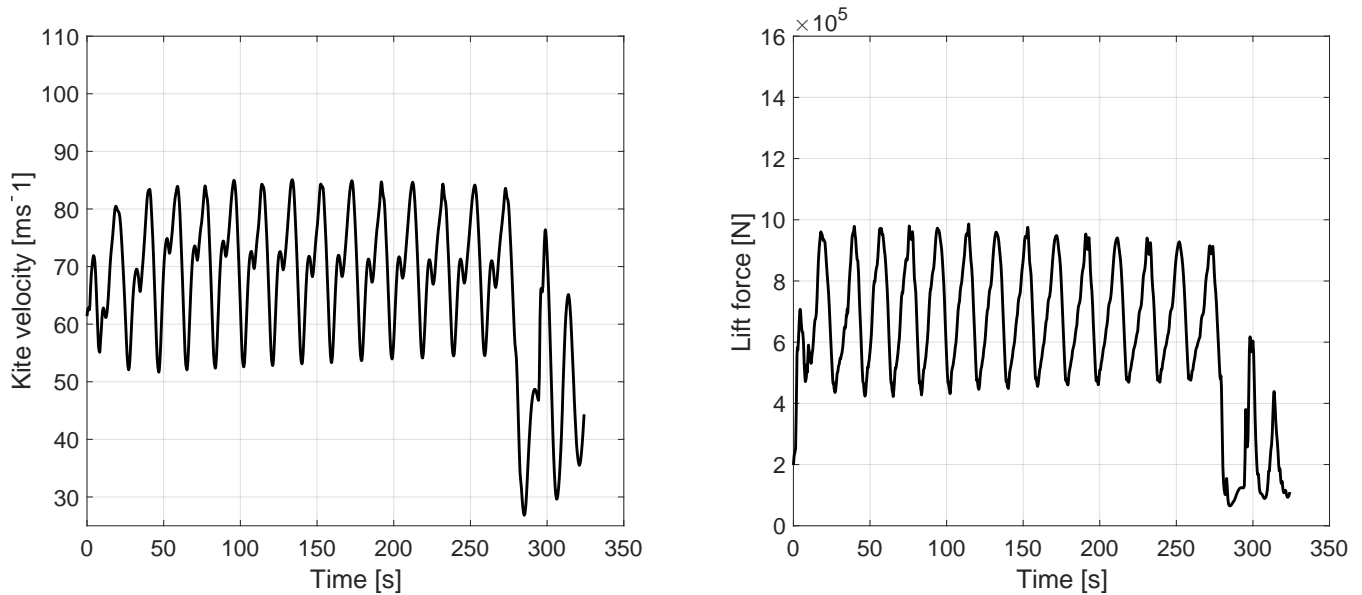


**Figure 13.** Figure-of-eight up-loop flight path of the most optimised solution set, 15 m/s wind speed. Left is the 3D flight trajectory, which is coloured by mechanical power. Right is the mechanical power with respect to cycle time.

assist using retraction, increasing overall power oscillation. The cycle average is at 1.344 MW, which is slightly lower than the  
 400 down-loop figure-of-eight but at worse power quality.

The converged up-loop trajectory under these conditions projected on the ground covers an area of  $1.24 \text{ km}^2$  ( $1.01 \text{ km} \times 1.24 \text{ km}$ ). This results in a surface area power density of  $1.08 \text{ MW km}^{-2}$ .

Figure 14 presents the velocity and lift force with respect to cycle time for the up-loop. Similarly to the other paths, the velocity and lift force follow the same behaviour.



**Figure 14.** Figure-of-eight up-loop flight path of the most optimised solution set, 15 m/s wind speed. Left is the kite velocity with respect to cycle time. Right is the lift force with respect to cycle time.

405 The maximum velocity is not exceeded at the start of the cycle; looking at the 3D flight path in Figure 13, this might not be specific to this flight path. It seems to be a result of the suboptimal transition phase, which just happens to be favourable for velocity. Unlike the down-loop, the higher velocity occurs in the centre, slowing down at the outer edge. Even though the velocity limits of the entire pumping cycle are closer to the average, during the traction phase, the average velocity is higher than for the other patterns.

410 The right of Figure 14 shows that the dominant load frequency of the lift force is approximately 0.052 Hertz. Out of the three studied patterns, this is the highest, having unfavourable effects on kite lifetime.

Table 3 gives an overview of the results discussed in this section. Putting the quantities side by side for easy comparison.

#### 4 Conclusions

This study systematically evaluated the performance of circular and figure-of-eight flight patterns for fixed-wing AWE systems  
 415 under consistent operational conditions. Through the development of a Matlab<sup>®</sup> Simulink<sup>®</sup>-based controller, the study achieved

**Table 3.** Summary of pattern performance of the three studied flight patterns using the MegAWES kite; Circle, figure-of-eight down-loop and up-loop.

	Circle	Figure-of-eight down-loop	Figure-of-eight up-loop
Cycle power	1.85 MW	1.39 MW	1.34 MW
PAPR	4.22	3.85	5.64
Ground area	0.63 km <sup>2</sup>	1.07 km <sup>2</sup>	1.24 km <sup>2</sup>
Surface area power density	2.94 MW km <sup>-2</sup>	1.30 MW km <sup>-2</sup>	1.08 MW km <sup>-2</sup>
Cycle duration	259.3 s	178.6 s	324.1 s
- Traction	230.3 s (88.8%)	158.8 s (88.9%)	279.0 s (86.1%)
- Retraction	29 s (11.2%)	19.8 s (11.1%)	45.1 s (13.9%)
Maximum kite velocity (traction)	83.74 m s <sup>-1</sup>	78.01 m s <sup>-1</sup>	85.07 m s <sup>-1</sup>
Average kite velocity (traction)	65.86 m s <sup>-1</sup>	63.13 m s <sup>-1</sup>	70.29 m s <sup>-1</sup>
Dominant load frequency (lift)	0.046 Hz	0.034 Hz	0.052 Hz

effective path tracking and demonstrated clear distinctions between these flight patterns in terms of energy output, power quality, structural load effects and spatial efficiency.

Unlike the results from the analysis on a small, lightweight kite, the heavy kite studied here had different power production levels over different patterns. The circular flight pattern yielded the highest cycle-averaged power output of 1.85 MW, outperforming both figure-of-eight patterns in energy capture efficiency. However, it required a smaller operational area, offering a power density of 2.94 MW km<sup>-2</sup>, which is substantially higher than the down-loop and up-loop figure-of-eight paths. These advantages make the circular path attractive for applications prioritising maximal energy capture within limited ground areas. It must be noted that there is some room to find solutions which reduce the average power output and improve the power quality.

Conversely, the figure-of-eight down-loop configuration demonstrated superior power quality, producing lower power oscillations with a peak-to-average power ratio (PAPR) of 3.85, compared to 4.22 for the circular path. This pattern also mitigated gravitational losses more effectively by leveraging optimal wind window positions during ascent. The up-loop variant, exhibiting the lowest cycle power (1.34 MW) and highest PAPR (5.64), suggests it is the least optimal flight path.

Additionally, each pattern displayed different factors which could impact structural fatigue and kite lifetime, driven by differences in load amplitude and frequency, as well as velocity profiles. The circular pattern showed a load frequency of 0.046 Hz in the traction phase. In contrast, the figure-of-eight down-loop configuration exhibited a lower load frequency of 0.034 Hz, beneficial for mitigating structural fatigue and potentially extending kite life. The up-loop had an even higher frequency and performed the worst. Furthermore, the amplitude of the force is generally lower for the down-loop compared to the other two. Nevertheless, fatigue should be studied in more detail to ensure a well-defined relation between pattern and cyclic loads.

In conclusion, the choice of flight pattern for AWE systems involves a trade-off between power density, power quality, and operational stability. Circular patterns are preferable for maximising energy output and spatial efficiency, while the down-loop

figure-of-eight offers a promising solution for applications where system longevity and smooth power output are critical for grid integration.

Future research should expand the optimisation domain, including adjustments to azimuth angles and more refined phase transitions, to further optimise power extraction and load management. Also, other wind speeds should be considered to evaluate if conclusions change throughout the complete wind speed domain.

*Code availability.* The reference design of the kite and the simulation framework is available on <https://github.com/awegroup/MegAWES> in open-access (release version 3.0). The specific environment and parameter inputs used in this work are made available on the 4TU database (Eijkelhof, 2025).

*Author contributions.* Conceptualisation, D.E., N.R. and R.S.; methodology, D.E., N.R. and R.S.; software, D.E. and N.R.; writing—original draft preparation, D.E.; writing—review and editing, D.E.; supervision, R.S.; funding acquisition, R.S. All authors have read and agreed to the published version of the manuscript.

*Competing interests.* At least one of the (co-)authors is a member of the editorial board of Wind Energy Science.

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