

WES article answer to reviewers

Dear reviewers,

Thanks for your involvement in reviewing our article. Both reviews received are answered sequentially.

The answers are structures as follows:

- *Reviewer comment*
- Author answer
- (Original paragraph/sentence)
- **Modified paragraph/sentence (with eventual additions in bold)** with indication of new line in updated manuscript

Reviewer 1:

GENERAL COMMENTS

This is an interesting and well-written paper, relevant to the airborne wind energy community. The authors develop a framework to simulate multiple ground-gen AWES with LES, while running a Model Predictive Controller. With this tool, they simulate a system from the literature and analyze the performances of two systems, where the second system is operated to avoid or to encounter the wake of the first system. The results show that the second system can be operated such that it almost entirely avoids the wake of the first, producing higher power.

I have minor reviews and a few suggestions for further analyses, which could be incorporated here or in future works.

Dear Reviewer,

Thank you for your careful reading of the manuscript and the positive comment. We appreciate your identification of the typos and inconsistencies. We have corrected the indicated errors and revised the text to improve clarity. We hope the manuscript is now easier to understand. We also complemented the text with the suggested analysis.

SUGGESTED ADDITIONAL ANALYSES

It would be nice to have a deeper explanation of how the aerodynamic force contributes to the reduction of wind speed for a Ground-gen AWES. Indeed, the wing is moving downstream, because of the reel-out, and generates an aerodynamic force. From the force of the lifting line and its velocity you should be able to reconstruct the work done on the fluid from the AWES. Note that this work should be directly comparable with the power available at the ground station, taking in account the work done by the tether drag, the change in kinetic energy of the AWES and the exchange of potential gravitational energy. These two last quantities are conservative, so that after a full

periodic cycle there should be a balance between the aerodynamic work and the electric energy. It would be nice to have some insights on the work done on the fluid from the AWES, which can hardly be reconstructed by the plots given in the paper because of the reel-out speed and of the kite attitude. This could provide a more detailed explanation on the skewed reduction in wind speed.

We thank the reviewer for the suggestion. Here we adopted an approach that relies on forces, as it then allows to obtain an estimate of the velocity deficit in the wake. This approach considers the averaged power cycle and is inspired by the actuator disk method. We distribute the time-averaged force on a surface, i.e. the time-average force equals the total force projected on the surface, to obtain the force density along the projected path. Here we only consider the streamwise component of aerodynamic force. Then the velocity deficit is estimated using the conservation of momentum.

We discuss this from lines 428 to 446:

Figure 15 shows the velocity deficit in cross-flow planes. The force density, based on `\texttt{AWEbox}` predictions, is plotted in Fig. 15(a). Its computation is inspired by the actuator-disk method. The streamwise (axial) force is distributed over a cross-flow plane such that the total distributed force equals the time-averaged axial force over one trajectory period,

$$\frac{1}{T_p} \int_0^{T_p} F_x dt = \int_0^L f_x ds, \quad \Rightarrow \quad F_x = f_x \|\dot{\mathbf{q}}(t)\| T_p \quad \Leftrightarrow \quad f_x = \frac{F_x}{\|\dot{\mathbf{q}}(t)\| T_p}$$

where F_x is the total instantaneous axial force acting on the kite, f_x corresponds to the axial force per unit length along the trajectory, and s is the curvilinear coordinate along the trajectory, with $ds = \|\dot{\mathbf{q}}(t)\| dt$. The trajectory has a total length L , and The force f_x is then distributed across the span and projected onto a surface.

A prediction of the time-averaged wake velocity can then be obtained using the conservation of momentum:

$$\frac{f_x}{b} = \frac{1}{2} \rho (U_\infty^2 - U_{\text{wake}}^2) \quad \Leftrightarrow \quad U_{\text{wake}} = \sqrt{U_\infty^2 - \frac{f_x}{b} \frac{2}{\rho}}$$

The associated velocity deficit is shown in Fig. 15(b). The axial force representation already provides insight into the wake shape. The velocity deficit is concentrated in the lower half of the loop and is slightly rotated clockwise, corresponding to the regions where the aerodynamic forces are largest. The estimation of the velocity deficit matches the deficit observed in the near wake, at $x=2D$. Further downstream, the velocity deficit is dissipated by the ambient turbulence and its intensity is reduced.

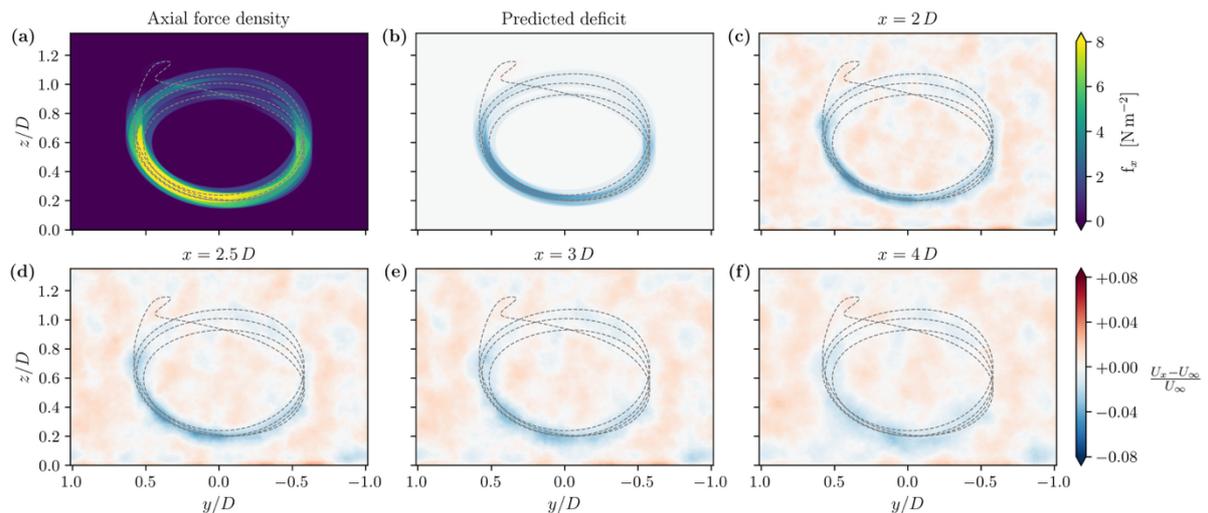


Figure 15: Six-cycle averaged streamwise velocity deficit of a single kite wake in transversal planes, at different positions downstream of the kite (c-f). The projection of the x-force density along the trajectory is represented in the upper left panel (a), along with the resulting velocity deficit prediction (b). The trajectory is indicated by dashed line.

A follower kite will therefore see a lower velocity in that area. This is also observed in Fig. 16 which shows the total aerodynamic force \mathbf{F}_a along the trajectory. The deficit decreases in intensity as it is advected downstream, while its shape remains essentially unchanged. The low averaged velocity deficit is due to the nature of the wake produced by such four-loops trajectory. Indeed, the loading of the kite is very low during the reel-in phase, which accounts for 30% of the trajectory time period, and the kite mainly produces a wake during the reel-out phase. The wake is therefore discontinuous in space and time, and released in batches, resulting in a low time-average velocity deficit.

DETAILED REVIEW

Line n. 1) Given that the journal is Wind Energy Science, I think it is not necessary to start the abstract with 7 lines of introduction. I would reduce it to max 2 lines.

The abstract and the introduction have been revised in that sense. Please directly refer to the updated manuscript or diff-document.

30) Please cite the original paper from Loyd

The citation was added. (L-21)

55) please use the same tense in all the manuscript. This should be proposes

This was corrected in the manuscript.

... Pynaert et al. (2023) **propose** a first classification of the different fidelity levels for aerodynamics and aero-elasticity. (L-44)

121) *A comment on Sect. 2.3 is missing*

This was added at the beginning of Section 2:

Section 2.3 presents the tether model used in this work, as implemented in AWEbox. (L-87)

Eq 6) It is not clear from the text why the non-dimensional coordinate s should be in front of the parenthesis. I believe it is because this expression comes from a moment equation: The moment at the ground station generated by the distributed drag (you right-hand-side times l) should be equal to the moment generated by the concentrated drag with the kite (you left-hand-side times l). It would be nice to have a brief explanation of this type, so that it is clear why s appears in the expression

We tried to clarify this. It does not come from a moment. It is there because the force on each element of the tether is shared between the ground station and the kite. The weighting factor for this sharing is s which is comprised between 0 and 1.

The factor s in front of the parentheses is introduced to weight the fraction of the total drag that acts on the kite. The other part acts on the ground station.

The weighting factor s specifies the fraction of the total tether drag attributed to the kite. For each infinitesimal tether element, the drag is partitioned between the ground station and the kite according to its position along the tether: a weight of $(1-s)$ applies to the ground station, and a weight of s applies to the kite. (L-167)

211) *remove "of which"*

Corrected

The AL is discretized into a set of N segments, at the center of each of which lies a control point.

The AL is discretized into N segments, **with a control point at the center of each segment.** (L-180)

219) *the citation should go inside the parenthesis ()*

Corrected (L-197)

229) even if the meaning of r and e is understandable (elevator and rudder), you could write it out, so there is no doubt

We added a line at the beginning of the paragraph (L-195):

Their associated quantities are denoted with the subscripts a , e and r , respectively.

235) Are the commas supposed to be multiplication signs? If yes, add the effective lift slope coefficient symbol in front for clarity

Supposed to be “\,” in Latex, it is a typo.

... yielding values of 1.01π for the elevator and 0.50π for the rudders.

... yielding values of $(dCL/da)_e = 1.01 \pi$ for the elevator and $(dCL/da)_r = 0.50 \pi$ for the rudders. (L-205)

245) is the chord-wise length of the aileron equal to 60% of the wing chord? that seems a lot compared to the wing drawing in the appendix.

This was not clear indeed; it is the efficiency factor which has a value of 0.6. Corrected.

where τ is the aileron effectiveness factor which depends on the fraction of the chord spanned by the aileron, ca/ci (here equal to 0.6), and $\eta = \eta(\delta a)$ is a correction factor to account for the reduced aileron effectiveness as the deflection angle increases, see (McCormick, 1995).

where τ is the aileron effectiveness factor which depends on the fraction of the chord spanned by the aileron, ca/ci , and $\eta = \eta(\delta a) < 1$ is a correction factor to account for the reduced aileron effectiveness as the deflection angle increases, see (McCormick, 1995).
In this case, $ca/ci = 0.25$ and $\tau = 0.6$. (L-214)

265) This should be a vector with square brackets. The $\hat{\omega}$ should be highlighted with `\boldsymbol`, in accord to the WES guidelines. Moreover, I would also add the dependence of the control inputs u on the time t .

Corrected (L-235) and in eq 10a

299) maybe refer to x_0 as $x(t=0)$? and eq 13d consequently.

To be even more explicit we changed the bounds of integration of eq 13a to t_s and t_s+T_H (instead of 0 and T_H) with t_s the simulation time at which the control evaluation is performed. ($t=0$ could refer to the start of the whole simulation).

We therefore adapted the other equations accordingly and notably eq 13d as:

$$x(t=t_s) = \hat{x}(t=t_s)$$

The old line 299 corresponds to the new line 268.

We also modified new line 259:

The prediction is done for a given time horizon T_H **starting at the current simulation time t_s .**

330) repetition of “the”

Corrected : The the number of AL control points => **The number of AL control points (L-300)**

334) Can you give a reference for the mollification width? It is still Trigaux et al (2024a)?

Yes, we added the reference. (L-304)

Fig 13 to 22) there is some text missing in the figures, for example in Fig13 a “B” in the legend and a “v” in the fig b y-label are missing. Please makes sure the figures are well-rendered in the manuscript.

Indeed, some symbols appear to be missing in the rendered preprint on the WES website. On my side, nothing is missing, neither in the files I saved from the submission nor in the compiled files. I have tried different figure generation settings in the hope of resolving the issue, which may be related to the font type. We will see if this is fixed in the next upload. I have re-generated Figures 13, 18, 19, 20, and 22.

Fig 14) here it seems that the wake is being partially deflected towards the ground a few D after the 4th loop of the trajectory. That makes sense because the aerodynamic force has a vertical component. It would be nice to add a comment on this and maybe to reproduce Fig 14b for different distances downstream.

An additional point on the discussion at line 445 might be that the kite fly the lower part of the loop always at the same altitude (probably because of some constraints in the MPC), while the altitude of the top part changes during the reel-out. This means that the loads are distributed over a larger swept area and thus lower induction can be found. However, I’m not sure if this effect is negligible. Other considerations might come from the suggested analyses.

Thanks for noticing this, we added this to the paper. Those aspects were already noticed in some of our previous work.

Starting line 416:

Three key features can be identified. First, the velocity deficit is predominantly located in the lower part of the trajectory. **This behavior has also been reported by \citet{Haas2019} and \citet{Crismer2023}, who also observed that the lower portion of the wake spreads more rapidly in the radial direction. In the present case, the weaker velocity deficit in the upper part of the wake can be partly attributed to the fact that the kite reaches different altitudes in the upper parts of the loops, whereas the lower parts reach the lower altitude bound and therefore occur at nearly the same altitude. However, this lower velocity on the upper part is also reported for purely circular single loop trajectories in \citet{Crismer2023}.**

Second, the wake is deflected downward. This deflection results from the tilted rotation plane and the presence of a vertical component in the aerodynamic force

acting on the kite. A similar effect is observed for tilted wind turbines \citep{Trigaux2020}.

465) I don't really understand the meaning of the term "2^e". Could you write it out? If it just stands for "second", then you could use "2'" or "2^{^{\circ}}" or "II".

Sorry it was the french superscript for second (fr: 2^e en: 2nd). We corrected it in "2nd". The figure captions are corrected accordingly. (L-461)

481) please write it out that the free stream velocity is 11m/s: ". is estimated to be approximatively equal to the free-stream velocity of 11 m/s"

The inflow velocity is 12 m/s. Here we mean the velocity in the wake is slightly lower. We clarified this.

Here, the advection velocity of the wake is assumed to be close to the mean velocity within the wake and is estimated to be approximately 11 m s⁻¹.

Here, the advection velocity within the wake is assumed to be **slightly lower than the mean inflow velocity** and is estimated to be approximately 11 m s⁻¹. (L-477)

495) if you refer here to Fig. 23, then you should explain it better. I think here you refer to Fig. 23 (a) and (b), where the in-phase cases are shown. Then please refer just to these two images, I tried to understand the figs (c) and (d), and the realized the explanation was at line 516.

We added the reference to the figure more explicitly. (L-492)

543) I don't really understand this sentence. An influence of -6% in power production is somehow relevant, and it is caused by the reduction in wind speed. Since the controller is in-the-loop you might not see it in flight speed. To clarify this aspect, you could add the numerical values of the period T_p of the various solutions somewhere in Sect. 5.2.2 (all plots show the normalized time, so we don't know the actual value of T_p). In alternative, you could also show a plot of the time evolution of the flight speed. For example, in Fig. 20b you show that the case phase-shifted has lower values of power, but it seems that it has the same flight speed as the loops have the same length.

We acknowledge that the sentence in the paper was perhaps not totally clear. The second kite produces less power because it experiences a lower wind speed due to the wake of the first kite. Despite this, it is able to track the trajectory correctly, so all states (position, velocity, etc.) match the reference. The trajectory period T_p corresponds to that of the reference trajectory and is 112 s. We modified the sentence in the paper to clarify it.

Concerning the trajectory tracking, the encountered wake perturbations do not affect the second kite significantly, and it is able to correctly track its trajectory. Nevertheless, there is an impact on the power production, of about -6 %, due to the velocity deficit of

the wake. We conclude that both the 6 % TI of the turbulent wind and the wake of the first kite are too small perturbations relative to the kite flight velocity to affect it significantly.

Concerning trajectory tracking, the encountered wake perturbations do not significantly affect the second kite **tracking** ability, and it correctly follows its trajectory.

Nevertheless, there is a **non-negligible** impact on the power production, of about -6%, **due to the reduced wind speed in the wake of the first kite**. We conclude that both the 6% TI of the turbulent wind and the wake of the first kite are too small perturbations relative to the kite flight velocity to affect **its tracking**. (L-557)

We also added this in line 377:

In the different plots, the time is made dimensionless using T_p , the reference trajectory period, which is 112s

Reviewer 2:

General Comments

The manuscript presents a high-fidelity numerical framework for simulating ground-gen AWES integrated with a MPC strategy. The authors validate the framework's accuracy regarding grid resolution and domain size. Subsequently, the study investigates two primary scenarios: a single kite and a tandem configuration of two kites. Key findings indicate that a downstream kite experiences only moderate power loss, even when operating directly in the wake of an upstream kite. The paper is well-structured, the methodology is clearly described, and the results are presented logically. The investigation into tandem flight offers valuable insights for future AWES layouts. However, there are specific aspects regarding inflow conditions and the interpretation of wake physics that require further clarification prior to publication.

Dear reviewer,

Thank you for your time, the reading of the manuscript, and your global positive appreciation of the work. We clarified what led us to use a uniform mean wind profile and further detailed the results regarding the waked kite configuration. We hope it is clearer now.

Specific Comments

1. Inflow conditions

The authors state that a uniform inflow wind condition (superimposed with Mann turbulence) is used, neglecting wind shear on the basis that the kite flies "relatively far from the ground." While this simplification effectively isolates the influence of turbulence, it removes a critical component of real atmospheric boundary layer physics. Even at altitudes between 200 m and 400 m (typical for the loops shown in Fig. 7), wind shear and veer can be significant, particularly in thermally stable conditions. Wind

shear creates an aerodynamic load asymmetry between the top and bottom of the loop, which the controller must compensate for.

The authors should discuss the potential impact of neglecting shear on both the controller's effort and the wake structure. Specifically, would the inclusion of shear significantly alter the vertical drift or recovery rate of the wake? If running a new simulation is computationally prohibitive, a discussion of this limitation and its implications is necessary in the text.

We agree with the reviewer that considering a uniform inflow is a simplification that neglects some physics if one wants to be the closest possible to a real scenario. Furthermore, the fact that the kite flies "relatively far from the ground." is not very accurate. The sentence is modified to be more accurate.

Prev. L 144: In the present study, the kite flies relatively far from the ground, and the mean wind shear encountered by the kite is moderate. It was hence decided to neglect wind shear and the wall, and to use Mann boxes, those being pre-generated using Hipersim (Dimitrov et al., 2024).

New L 111: The present study focuses on the ability of the kite and its controller to maintain stable flight in turbulent flows and under external perturbations, such as the wake of another kite. To isolate the turbulence and wake effects, it is chosen to consider a uniform mean inflow, and synthetic turbulence using Mann boxes pre-generated with Hipersim (Dimitrov2024).

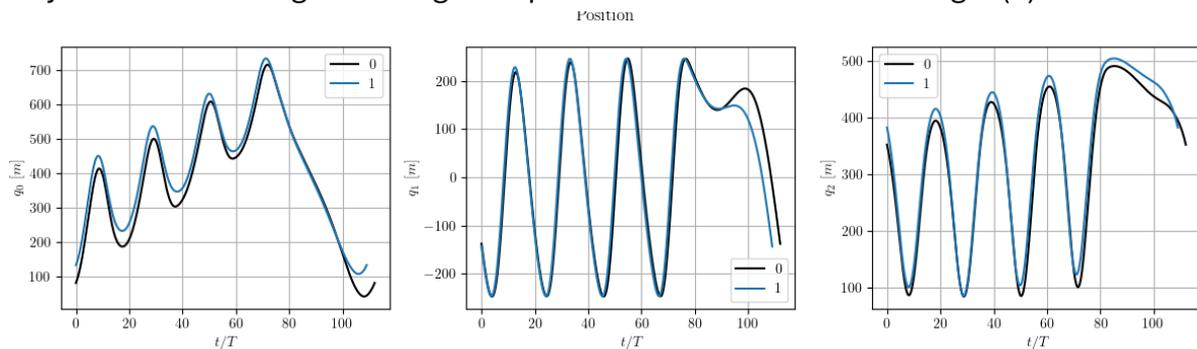
Regarding the trajectories, they are optimized by AWEbox given a mean wind profile. Considering wind shear would thus have an impact on the resulting trajectory. It could lead to the kite flying higher. However, it is a tradeoff between tapping into higher wind speeds and limiting the tether losses due to the tether length and limiting the elevation angle. The loading on the kite will also be different.

Another aspect is the use of the synthetic pre-computed turbulence. Imposing such turbulence together with a sheared inflow is not straightforward if a physically consistent representation is sought, as it would require a careful rescaling of the turbulence field to preserve its spectral distribution and coherence.

Furthermore, we believe that considering a uniform wind instead of a shear inflow will not have a large effect on the controller. The trajectory is generated using AWEbox considering the mean wind profile and the loading variation along the trajectory is already large in the case of the uniform mean wind (see Fig 12b). The kite is expected to be able to accurately follow its trajectory when subjected to the mean wind profile which was used to optimize the trajectory. The LES simulations would allow to study the impact of the TI variation with altitude which would be observed in the presence of shear but the present study tends to show that the impact of atmospheric turbulence

on the tracking performance is limited. Regarding the wake, it will certainly be affected to some extent by the non-uniform velocity profile. It is however difficult to estimate the impact a priori. It would therefore be interesting to study the trajectory variations depending on the wind conditions, and then the impact of such changes on the wake. But this constitutes a study in itself and is not the subject of the present paper. It is left for future work.

Here below, we present a comparison on the positions for a trajectory using the same parameters as in the paper and the uniform inflow à 12 m/s (0) and a trajectory where only the wind is changed to a log wind profile with 12 m/s at 250m height (1) :



The kite flies indeed slightly higher, as seen from the third plot (q_2), but only by ~ 30 m.

The paper was modified as follows. A comment on the wind assumptions and impact on the trajectory is also added:

New L-341: It should be noted that the trajectory is optimized for the given set of parameters and would therefore differ for other wind profiles. In the case of a uniform inflow, the kite flies at the lowest feasible altitude to limit the tether length and elevation angle. For a sheared inflow, the altitude-dependent wind velocity also plays a role, and the optimal trajectory may reach higher altitudes because of the lower wind speed near the ground. However, increasing the tether length and the elevation angle is detrimental to power production because it increases aerodynamic drag. There is therefore a trade-off.

And in the conclusion:

New L-568: It should also be noted that assuming a uniform inflow may affect the wake behavior compared to a sheared inflow. This aspect is therefore left for future investigation.

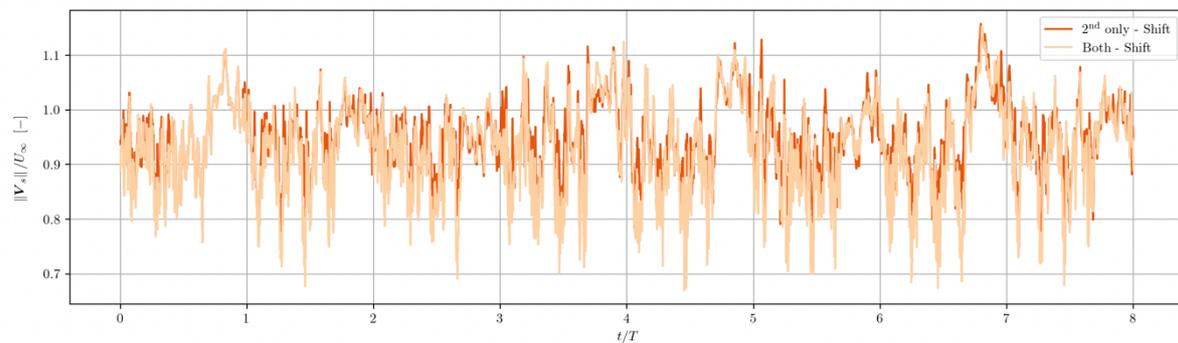
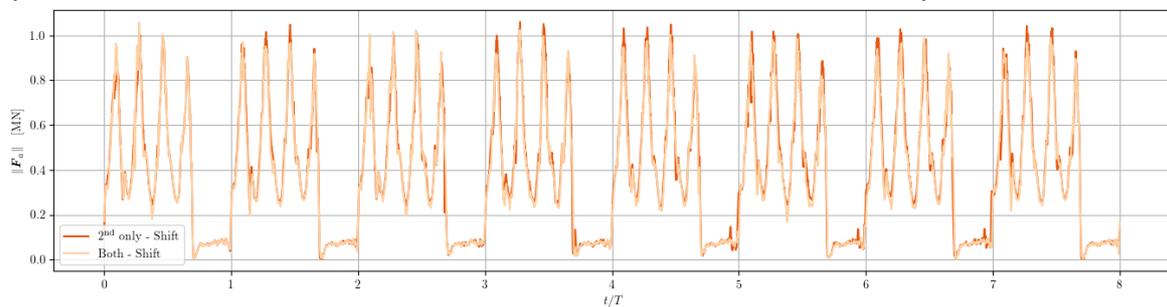
2. Wake transient effects

The analysis relies on six-cycle averaging to quantify velocity deficits. As noted by the authors, the wake is discontinuous and released in discrete batches. Time-averaging a pulsed, moving wake tends to smooth out the intensity of the vortex structures. A

follower kite does not experience an "average" wake; rather, it interacts with specific, localized vortex structures.

In phase-shifted configuration, could the authors provide a plot showing the instantaneous forces (or effective velocity) experienced by the second kite during the specific moments it traverses the wake? This would better quantify the load transients that the controller must handle, which are more critical for structural fatigue than the reported 6% average power loss.

The instantaneous evolution of the force and effective velocity are provided here below. They naturally exhibit large variations due to the basic kite working principle with added perturbations due to the turbulence. However, it is difficult to distinguish and isolate specific transient loads due to the encounter with the wake of the upstream kite.



Instead, we added cycle average forces and velocity (as sampled from the AL) and compared them, as well as the standard deviation, to emphasize the effect of the first kite wake on the second kite. However, there is no large load transient added from flying in the first kite wake, which might be due to the relatively high velocity of the kite compared to the induced perturbation, as explained in the paper.

Here is what we further added/developed from line 506 to 531:

The second kite also flies well and its tracking ability is only weakly affected, despite the perturbations it encounters, as evidenced by the "Shift" curves in Fig 20. In Fig 20(a), the tracking error of the flown path with respect to the reference remains very small and does not exceed the error observed in the other cases. Indeed, the kite flies quite fast, and perturbations must be large enough compared to its velocity to become significant. For example, the turbulence intensity is evaluated with respect to U_{∞} which is six

times smaller than the mean kite speed during its reel-out phase. Turbulence levels expressed this way are therefore much less significant for the kite, which may explain why the kites are only weakly perturbed.

Similarly, the error on the force, shown in Fig. 20(b), is of the same order of magnitude as in the other cases. As evidenced in Fig. 24, the aerodynamic force on the second kite is globally lower when it is in the wake of the first one. However, characteristic features are hardly identifiable. The evolution of the standard deviation of the aerodynamic force is also shown for both cases, and again no significant increase is observed. The RMS difference in terms of forces, evaluated on instantaneous data, goes up to 29% of $\max(F_a) = 1.06$ MN while it is only 3% on average.

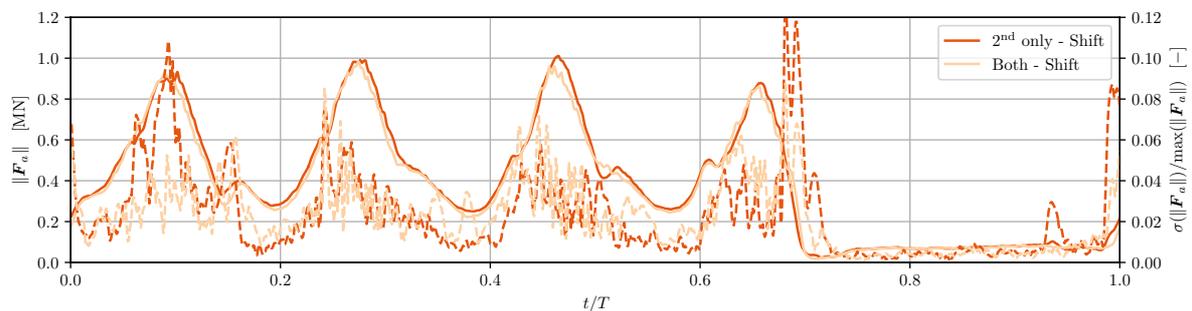


Figure 24: Six-cycle averaged aerodynamic force magnitude (solid line) and standard deviation (dashed line) for the second kite flying with or without the first kite in front, in

What the second kite effectively perceives is a modified inflow velocity. The flow velocity it experiences is obtained from a simulation in which the force distribution in the flow is switched off, and the second kite is used as a sensor. This prevents the measurement from being perturbed by the bound vortex and wake of the AL. The results are shown in Fig. 25 for the second kite flying alone and when in the wake of the first kite. Figure 25(a) shows that, overall, the sampled velocity is slightly lower throughout the reel-out phase. The standard deviation of the measured flow velocity, as provided in Fig. 25(b), also increases slightly. Figure 25(c) shows that the difference in sampled velocity is largest when the aerodynamic force is highest, around $t/T \sim 0.1, 0.28$ and 0.45 , which corresponds to the portions of the trajectory where the kite is on the bottom of the loops. This is also where the velocity deficit in the first kite's wake is primarily located. The difference in sampled velocity ranges from 0% and 12% of the inflow velocity. Similarly, the increase in standard deviation occurs mainly when the kite is at the bottom of the loops during the reel-out phase, and ranges from 0% to 8% of the inflow velocity. The RMS difference in terms of sampled velocity, evaluated on instantaneous data, goes up to 26% of the inflow velocity while it is only 3.6% on average.

Again, this difference in sampled velocity is made dimensionless using the inflow velocity and is thus even smaller when compared to the kite flight velocity.

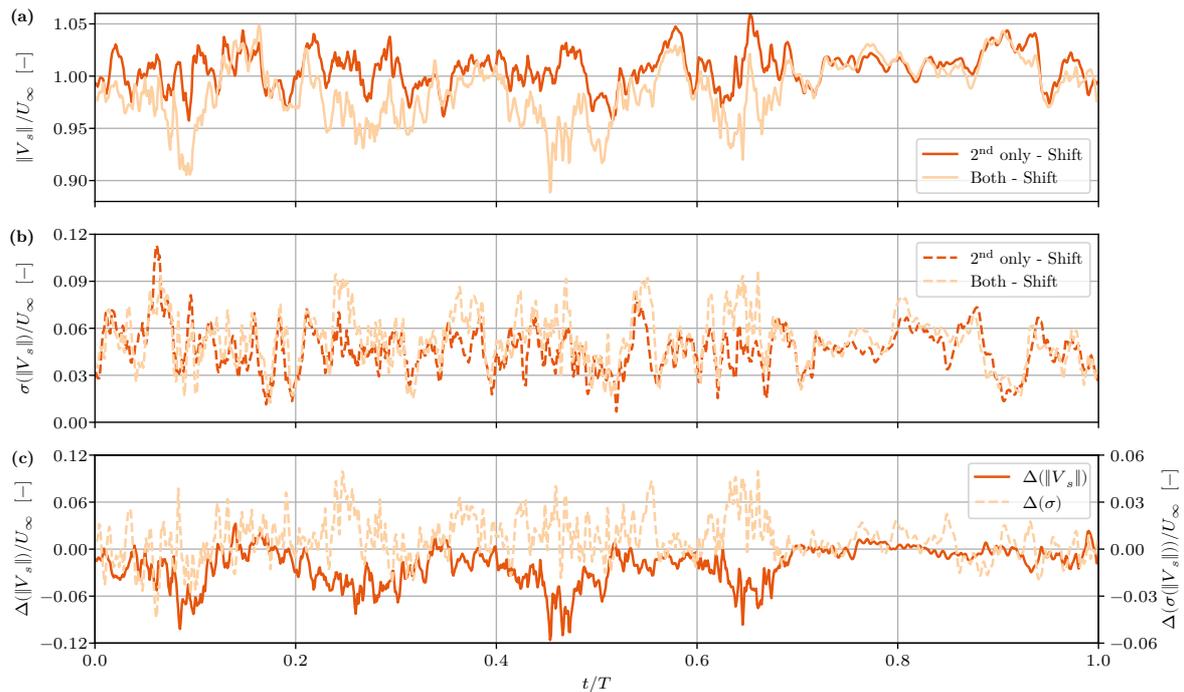


Figure 25: Six-cycle averaged mean sampled velocity on the wing (a) and its standard deviation (b) for the second kite flying with or without the first kite in front, in LES with AL in a 6% TI flow. The second kite is here used as a sensor and does not induce forces in the flow to have avoid the measures to be perturbed by the wing bound vortex and wake. The differences between the cases with and without the first kite is also displayed (c).

The velocity deficit induced by the wake of the first kite nevertheless affects the power production of the second kite.

Technical Corrections

1. *Abstract and Introduction: The broad overview of the general wind energy context in the Abstract and Introduction is somewhat lengthy. I recommend condensing this background material to focus more quickly on the specific challenges of AWES wakes and control.*

The abstract and the introduction have been revised in that sense. Please refer to the updated manuscript.

2. *Line 16: "foor-loop" should be corrected to "four-loop".*

Corrected (L-14)

3. *Line 465: "latter referred as" should be corrected to "hereinafter referred to as" (or simply "hereafter").*

Corrected (L-465)