Investigation of blade flexibility effects over the loads and wake of a 15 MW wind turbine using a flexible actuator line method

Reply to reviewer 2

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We first would like to thank the reviewer for the insightful comments. All these comments have been addressed. The detailed reply is presented hereunder, as well as the suggested changes to the manuscript. The reviewer can also refer to the updated version of the manuscript, where all the changes are highlighted.

"Investigation of blade flexibility effects over the loads and wake of a 15 MW wind turbine using a flexible actuator line method" investigates the effects of blade flexibility on the forces and wakes of the IEA 15-MW wind turbine, using a LES simulation with the actuator line method (ALM) coupled with a blade structural dynamics solver. Three models for the turbine are considered: rigid undeformed blades, rigid deformed blades and flexible blades. For the case with uniform inflow, with and without turbulence, the results are compared to the results of a BEM (blade-element momentum theory) model and a free vortex wake method. The turbine is also simulated in a neutral atmospheric boundary layer.

The detailed analysis of this work includes the analysis of the distribution of forces and displacements using different methods and flexibility models, in time and frequency domains, in addition to characteristics of the wake. It is a clear contribution to the field of research and within the scope of the journal. The manuscript is well-written, with clear objectives. The results are original, with associated discussions of high scientific relevance. There are a few remarks that should be addressed before publication, please see below.

Reply Thank you for your appreciation. We have addressed the comments, and the detailed reply is provided hereunder.

Comment 1 In lines 93 and 465: reference to "advanced" ALM. However, this concept of "advanced ALM" is ill-defined. For example, previous works (Churchfield et al., 2017) have defined it by a collection of developments, however, not all of these developments seem to be implemented in the present work. Also, "advanced" may be interpreted as a common adjective, because it is not capitalized. In that sense, the concept of "advanced ALM" is questionable in the present context. For these reasons, I suggest that the term "advanced" be avoided.

Reply The term "advanced" is removed from the manuscript.

Comment 2 In line 107: The mentioned corrections are not simple tip corrections, a more modern term is "smearing corrections", because they correct for the smearing of the forces, not only at the tip. If you prefer to be more specific to this class of smearing corrections based on vortices, one usual term is "vortex-based smearing corrections".

Reply The term "tip correction" is changed to "vortex-based smearing corrections", as suggested, to avoid the confusion with tip corrections developed for the BEM or for the actuator disk method.

Comment 3 In line 111: The use of "much" in "much decreasing the need for a tip correction" might be misleading. It decreases the need for a correction, but not by orders of magnitude. Despite having a lower error than a 3D Gaussian, Caprace et al. (2019) showed that there is still a relevant error if using the 2D Gaussian without any correction.

Reply We agree that even using a 2D Gaussian mollification, the accuracy of the ALM remains problematic in the near tip region. It is however significantly better than that of the ALM with 3D Gaussian mollification (e.g., Mikkelsen (2004); Jha and Schmitz (2018); Caprace et al. (2019)). Nevertheless, "much decreasing" was modified to "decreasing".

Comment 4 In line 181: A wake length of 10 rotations without a far wake model might be too short. Please show that this choice of parameters does not have an effect on the distribution of forces (results of table 1 and figure 4).

Reply The choice of 600 panels is based on the OLAF model currently provided in the repository for the IEA-15 MW [1]. This model suggests the use of 600 near wake panels, without far wake. Yet, we agree with the reviewer that 10 rotations is the minimal wake length suggested in the guidelines, and a verification of the impact of this parameter is therefore necessary.

The OLAF simulations are thus performed with 1024 near wake panels (around 17 rotations) in the flexible case and the obtained force distribution is depicted in Figure 1. The increased number of panels do not lead to any visible change in the force distribution in the case. As a result, the obtained C_T changes from 0.813521 with 600 panels to 0.813518 with 1024 panels, and the C_P varies from 0.600634 to 0.600631. Both Table 1 and Figure 4 are thus unaffected by the length of the near wake.

The result with 1024 panels are thus presented in the paper, and a mention to this verification has been added in the revised version:

This wake length was verified to be sufficient in this case to provide a converged force distribution on the blades by comparing to simulations with shorter near wake with 600 panels extending for 10 rotations, which led to the same results.

Comment 5 In figure 4: The results from OLAF show a small peak near the tip, which looks unusual. Please explain it and show that it is not dependent on the choice of parameters.

[1] https://github.com/IEAWindTask37/IEA-15-240-RWT/tree/master/OpenFAST/IEA-15-240-RWT-OLAF

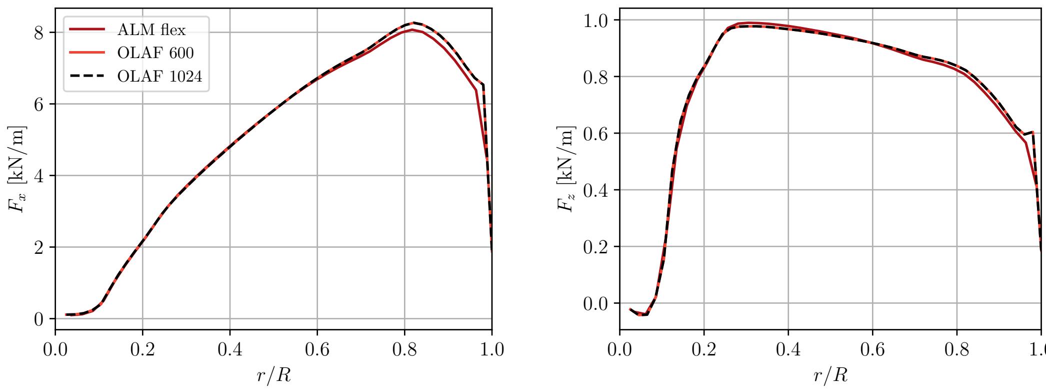

Figure 1: Steady state aerodynamic loads in the blade root frame for the flexible cases: ALM (dark red), and OLAF with 600 (light red) and 1024 near wake panels (dark dash).

Reply This peak arises from the regularization of the trailing vortex filaments using OLAf. It is similar to what is generally observed for the ALM with 3D mollification (see e.g. Meyer Forsting et al. (2019)). Due to the vortex filament regularization in the spanwise direction, the velocity induced by the trailing vortices decreases near the blade tip. This leads to a lower induced angle of attack and therefore to higher forces near the tip. The presented ALM does not show such a peak thanks to the use of a 2D mollification.

Since this peak is related to the regularization of the vortex filaments, it is affected by the parameters of the regularization. The parameters suggested in the reference IEA-15 MW model were used, as mentioned in the original manuscript : *"The vortex core is regularized using the Vatistas vortex model*[2] *with the optimized parameters option"*. The current implementation of the optimized parameters in OLAF consists in setting the vortex core radius r_c as twice the size of the spanwise spacing between the blade nodes Δs, hence here $r_c = 2\Delta s$, with $\Delta s \simeq R/50$. If one reduces the core radius to $r_c = 0.6\Delta s$, as suggested in the OLAF guidelines, the peak decreases but remains visible, as depicted in Figure 2. Similarly, if the node distribution changes and that the regularization scales with the spanwise discretization, then it will affect the peak at the tip.

We added a mention to the size of the regularization parameters in the set-up description: *The vortex core is regularized using the Vatistas vortex model with the optimized parameter option, which corresponds to using $r_c = 2\Delta s$ where Δs is the mean spanwise spacing between the aerodynamic nodes. Clearly, the regularization parameter can noticeably affect the force distribution, especially near the tip.*

The comment of the result has also been extended to discuss the effect of the regularization in more details:

The only noticeable difference between the two methods is the small increase of the forces near the blade tip, which is more pronounced using OLAF. The latter is due to the regularization of the trailing vortex filaments, which decreases the induced velocity near the tip. To a smaller extend, the ALM also depicts a slight increase of the lateral forces (i.e., F_z, in the blade root frame) at the tip due to the mollification (i.e., the smearing of the shed vortices (Caprace et al., 2019)). It is however less pronounced thanks to the use of the 2D mollification, without spanwise

[2] By the way, this model goes back to the regularization by Rosenhead (1935) of point vortices, where $1/r = r/r^2$ is replaced by $r/(r^2 + r_c^2)$ and should not be refered to Vatistas.

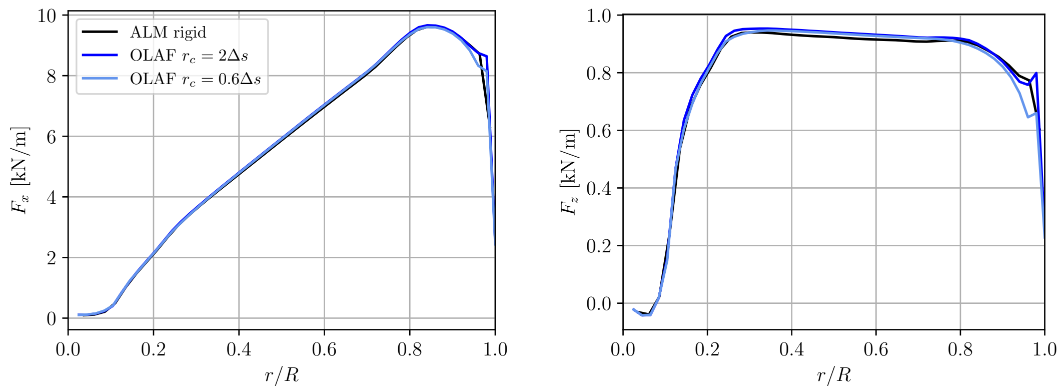

Figure 2: Steady state aerodynamic loads in the blade root frame for the IEA-15 MW with rigid blades: comparison between the ALM (black), and OLAF with two different regularization sizes.

smearing.

Comment 6 In line 202: Please define "lateral forces".

Reply A definition was added: *lateral forces (i.e., F_z, in the blade root frame).*

Comment 7 In line 205: Please cite (Caprace et al., 2019) when mentioning the error of the mollification of the ALM. That work clearly showed an error in the induced velocity for the choice of smearing used in the present work (2D Gaussian).

Reply The reference has been added. (By the way, this paper is from our research group)

Comment 8 It is relevant to cite (Mikkelsen, 2004) in the introduction and in the discussion of section 3.1 (lines 202 to 206). This work showed, in 2004, that an uncorrected 2D Gaussian had better results than an uncorrected 3D Gaussian. Also, the same work showed that the ALM with a 2D Gaussian regularization without tip correction predicted higher forces than methods (ALM and ADM) with Prandtl's (or Glauert's) tip correction. (Mikkelsen, R.F., 2004. Actuator disc methods applied to wind turbines, PhD Thesis, DTU, Chapter 8).

Reply Thank you for suggesting this reference. It is indeed relevant and has been added in Section 2.2 in which the ALM with 2D regularization is presented.

Comment 9 In lines 230 to 235: It is mentioned that the blade natural frequencies are calculated using the undeformed configuration. However, the flexible blades oscillate around the mean deformed configuration. For a non-linear solver such as BeamDyn, are the differences in the natural frequencies negligible?

Table 1: Natural frequencies (Hz) of the IEA-15 MW reference wind turbine obtained using BeamDyn for the blade rotating at 6.45 RPM.

	Undeformed	Deformed
1st Flapwise	0.518	0.516
1st Edgewise	0.736	0.734
2nd Flapwise	1.361	1.356
2nd Edgewise	2.547	2.538
3rd Flapwise	2.860	2.849
3rd Edgewise	4.625	4.607
1st Torsion	4.832	4.815

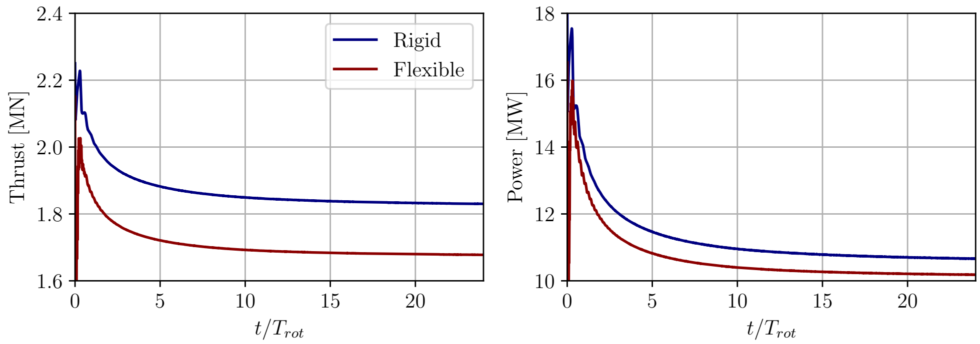

Figure 3: Evolution of the thrust and power with the number of rotation for the IEA-15 MW turbine with a uniform inflow velocity of 9 m/s.

Reply There is indeed a small effect of the deformation over the blade natural frequencies, as shown in Table 1. This Table compares the natural frequencies obtained using the undeformed blade position to those obtained by linearizing around the mean deformed configuration. The impact of the deformation over the natural frequencies is very limited, such that it can be considered negligible.

We added a mention to this investigation in the revised manuscript :

The blade natural frequencies are also depicted. These were obtained using the mass and stiffness matrices provided by BeamDyn in the rotating undeformed configuration, without accounting for the coupling with the aerodynamic loads. It should be noted that, for a non-linear beam solver, such as BeamDyn, the blade natural frequencies are slightly affected by the deformation. This difference was here verified to be negligible, such that the natural frequencies do not need to be updated using the blade deformed configuration.

Comment 10 In line 269: It is not clear that the value of 20 rotations for the discarded time is sufficient to reach a statistically stationary flow (it seems to be much lower than one flow through time). Please show that this choice does not affect the statistics.

Reply The convergence of the loads was tested in uniform flow according to the set-up presented in Section 3.1. The evolution of the power and thrust with the number of rotation is depicted in Figure 3. From rotation 20 to rotation 22, the thrust decreases by only 0.20% and the

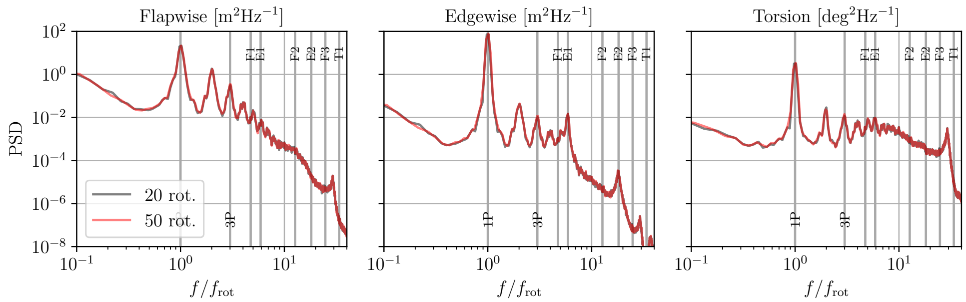

Figure 4: Power spectrum of the tip displacements for the IEA-15 MW turbine in ABL. Statistics are started after 20 or 50 rotations.

power decreases by 0.15%, which indicates that 20 rotations are sufficient to obtain statistically converged loads on the rotor. Twenty rotations is around 167 s, which is indeed smaller than one flow-through time (here, 0.58 flow-through time). For the loads, it is however not necessary to perform a full flow-through time to reach statistical convergence, since the far wake has a limited impact on the aerodynamics. The PSD of the displacements (Figure 6 of the original manuscript) was obtained by discarding the first 20. To verify the statistical convergence, it was re-computed by discarding the first 50 rotations. The differences are very small, as depicted in Figure 4.

This verification is mentioned in the revised manuscript :

The 20 first rotations are discarded as the wake induction is not yet converged. The power, thrust and power spectra of the loads were indeed verified to reach statistical convergence after 20 rotations.

Comment 11 In line 394: Analogously to the previous remark. Please show that this choice of "last 150 rotations" does not affect the statistics. How many flow through times were discarded?

Reply The 50 rotations have a duration of 417 s, corresponding to 1.45 flow-through time. This provides a sufficient buffer for the transient part of the wake to leave the computational domain. This is illustrated in Figure 5 which shows the velocity in the wake of the turbine at different normalized time $t^* = t\,U_{hub}/L_x$, where $L_x = 12D$ and $U_{hub} = 10$ m/s. One clearly observes that the transient part of the wake has reached the end of the domain for $t^* = 1.5$. Additionally, Figure 6 (corresponding to Figure 13 of the original manuscript) compares the velocity deficit and the turbulent kinetic energy profile obtained by collecting the flow statistics discarding the first 50 or the first 100 rotations. The statistics are quite similar, especially in the near wake. Some slight differences can be observed downstream, and result from the smaller averaging window. Clearly, these changes do not affect the discussion of the results in the original manuscript.

We mention this verification in the revised manuscript:

The wake statistics are first considered. The statistics are computed over the last 150 rotations, to ensure that the wake is developed up to the end of the computational domain before averaging. The discarded first 50 rotations corresponds to approximately 1.5 flow-through times, which was verified to be sufficient to reach a statistically converged flow. The averaging window of 150 rotations then corresponds to approximately 4.4 flow-through times.

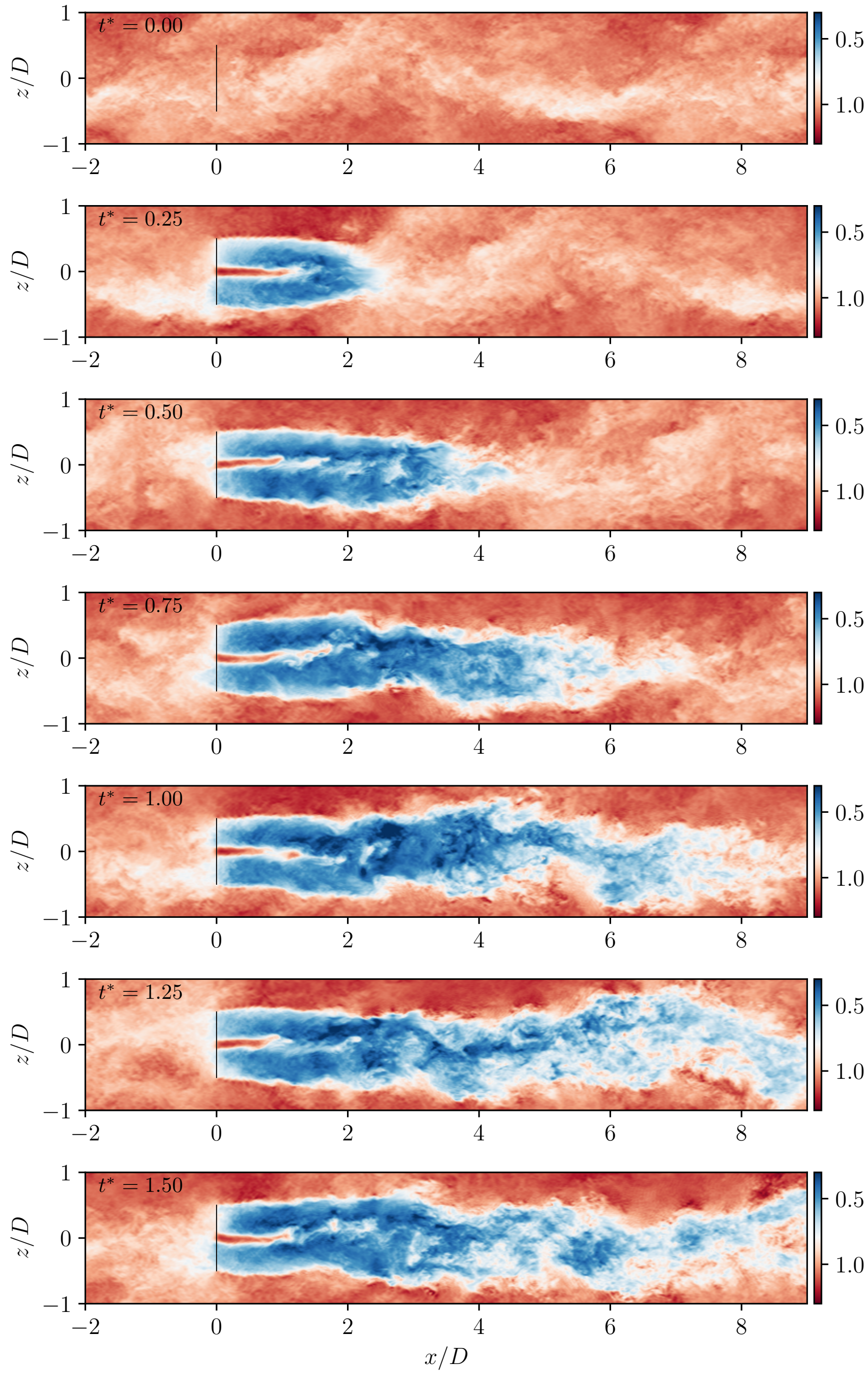

Figure 5: Instantaneous velocity in the horizontal plane crossing the rotor hub (bottom view).

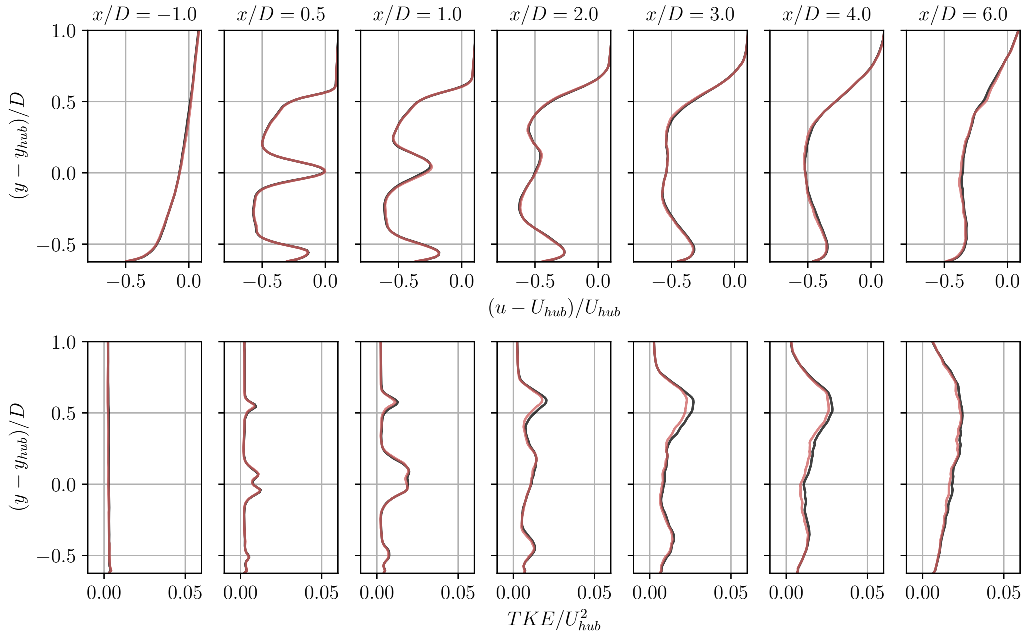

Figure 6: Profiles of mean velocity deficit (top) and turbulent kinetic energy (bottom) in the near wake of the turbine at various downstream locations. The flow statistics are obtained by discarding the 50 first rotations (black) or the 100 first rotations (red).

References

Caprace, D.-G., Chatelain, P., and Winckelmans, G.: Lifting line with various mollifications: theory and application to an elliptical wing, AIAA Journal, 57, 17–28, 2019.

Jha, P. K. and Schmitz, S.: Actuator curve embedding–an advanced actuator line model, Journal of Fluid Mechanics, 834, R2, 2018.

Meyer Forsting, A. R., Pirrung, G. R., and Ramos-García, N.: A vortex-based tip/smearing correction for the actuator line, Wind Energy Science, 4, 369–383, 2019.

Mikkelsen, R. F.: Actuator disk methods applied to wind turbines, 2004.