

Final response to referee comments

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To begin, I want to thank the referees for their valuable comments on the provided manuscript. We believe that addressing these comments will contribute to the quality of this paper greatly. Moreover, we thank the Copernicus editorial team for their support through this process. In the following, the reviewers' comments are presented followed by our answers in blue. Minimal changes have been applied to the comments to make them compatible with the used text editor. The numbering of figures used in our answers refers to the order in our original submission. Please note that this has changed in the revised version.

The changes are then applied to the manuscript accordingly. To make it easier to follow these, they are colored blue in the revised manuscript. However, for the final manuscript, we will follow the formatting style of the journal. Some minor errors related to typos or formatting are also corrected but not colored. In addition to addressing the referees' comments in the revised manuscript, other changes are applied to the text to enhance the quality of the paper. These are also colored in blue.

1 RC1

This manuscript presents a comparison between the actuator line model (ALM) and the actuator sector model (ASM). The article presents interesting insights on the effect of changing the sampling location and time-step in the ASM. There is a fundamental drawback in the method/approach used and the comparisons presented in the manuscript. The authors fix the value of epsilon to $\epsilon=2dx$ in their study. This choice limits the validity of the study in 2 ways (<https://doi.org/10.1002/we.1747>):

1. The results are not expected to converge because $\epsilon/dx=2$ is not enough resolution to resolve the aerodynamics of the blade for that epsilon. The recommended values to be within less than 1% for converged quantities along the blades is $\epsilon/dx \geq 5$.

Answer: The objective of the study is to suggest an implementation method for ASM that would result in a “converging behavior” when the results are compared to ALM. This means that the relative error for power and thrust values compared to ALM are kept within an acceptable range for different mesh resolutions. The usage of the term “converging” in the manuscript is meant this way. We will emphasize this further in the manuscript. Moreover, the choice of ϵ is made mainly based on two criteria. The first one is to avoid numerical instability for lower values of ϵ . The second reason is that using a large value of ϵ such as $\epsilon/dx \geq 5$ would result in over-smearing of the body forces in such a way that the tip vortices are not created even for a mesh resolution of 64 cells along the rotor diameter (Martinez et al., 2012; Martínez-Tossas et al., 2015). A choice of $\epsilon/dx=2$ is recommended by Troldborg (2009) based on extensive sensitivity analysis for the value of ϵ for ALM. This is also pointed

out by Martínez-Tossas et al. (2015) that an $\epsilon/dx \geq 2$ is required to ensure an oscillation-free solution. Since ASM is basically a sweeping actuator line or a multi-bladed turbine implemented with ALM, in our judgment, the result of these studies could be applied in our case as well.

30 2-By fixing $\epsilon/dx=2$, the value of epsilon changes with the grid. Every time the grid is changed, the definition of the problem changes because epsilon is changed. This also leads to differences along the blade of at least a few percent. I recommend the authors to assess these drawbacks and reevaluate the manuscript.

Answer: As explained, the study aims to suggest an implementation for ASM that produces similar results to those obtained by ALM for different mesh resolutions as users may select a different mesh resolution depending on the objective of their study and available computational resources. The motivation is to make sure that the user of the proposed ASM model can be confident that the results obtained by ASM will have an accuracy comparable to ALM for a wide variety of mesh resolutions. Therefore, although the value of ϵ changes –thereby changing the problem– the results are compared with their ALM counterpart of the same mesh resolution and ϵ , fulfilling the objective of the comparison.

Specific comments: The authors dive into the topic of tip corrections, but this is yet another source of error/difference for the simulations. The results presented have many sources of error and they all contribute to the blade aerodynamics, which makes it too difficult to draw conclusions. The authors are trying to attribute the differences to the choice of sampling location or the width of the ALM, but there are also differences because of the grid resolution and size of epsilon.

Answer: The purpose of the section for tip/smearing correction is to find out, among the considered methods, which one results in the closest results compared to ALM of the same mesh resolution and the same ϵ value. The smearing correction used for ALM is already validated thoroughly (Meyer Forsting et al., 2019). Therefore, it has been used as a baseline to compare the results of the proposed ASM. In addition, to emphasize further, the results of ASM are compared with ALM of the same mesh resolution and ϵ value. Therefore, it is not a major source of difference/error. Moreover, the results of the proposed ASM with the suggested sampling method and smearing correction are the closest to ALM thereby achieving the objective of the study.

“As can be seen in Fig. 2, the power and thrust values have decreased with each refinement for the OP approach, as the forces become more concentrated due to the decreased value of epsilon which is proportionate to the cell side length” Comment: These figures are showing that there is a grid convergence problem and should not be confused with the old/new velocity sampling. Is epsilon changing as the grid is refined? Can you provide some details of the simulation before showing results?

Answer: The purpose of presenting Fig. 2 is not to evaluate the convergence of ALM but to show that there are two conceivable ways to update the rotor state and depending on which one is selected, the results are different compared to each other. Fig. 2 also uses BEM results to show that although the choices for updating the rotor states are different the results are comparable in both cases with BEM results for different mesh resolutions. Therefore, this motivates why we have considered both of these updating schemes for ASM as well. In the revised manuscript, we have changed the language in a way that this is more clear.

In addition, an extra discussion is made in the revised manuscript regarding the results from ASM with NP approach. It explains that as the only acceptable NP-ASM results are the ones obtained by sampling the velocity from the sector beginning, and this is equivalent to sampling the velocities from the sector’s end with OP approach, it can be argued that sampling the velocities from the sector’s end produces the closest results to NP-ALM. As mentioned in section 2 (line 81) all simulations in

this study are done using $\epsilon=2dx$. This also applies to the simulations used to produce Fig. 2. We will summarize the details of all the conducted simulations in tables as suggested also by Referee 2 in the Appendix.

65 “Regarding velocity sampling, in ALM, the velocities are sampled on the location of the blade points for each blade. However, in ASM, more methods are conceivable” Comment: There are other methods to sample the velocity in the ALM. Please expand the literature review and cite the work in this area.

Answer: This has been a mistake and we will correct this in the revised version of the manuscript. It should have been instead: “Regarding velocity sampling, in ALM, the velocities are usually sampled based on the location of the blade points for each blade” in which “are sampled on” is replaced with “are usually sampled based on”. We have also added a few examples of
70 how this is done in the literature in the revised manuscript. The reason why the sampling is done along the actuator line points is that since an isotropic 3D Gaussian function is used to project the forces in the flow domain, the location of actuator line points for the OP approach coincides with the center of the bound vorticity where the flow is not influenced by the blade-local flow effects for low drag values (Martínez-Tossas et al., 2017). Moreover, an explanation is added as to why this is not the case for ASM since the cumulative body force projection from all lines within a sector does not result in a circular cross-section for
75 the bound vorticity. This also motivates why different velocity sampling methods are tested to investigate which one resembles ALM results to a better extent for different mesh resolutions.

“Each case is run for 600 seconds as it is seen the thrust and power values do not change considerably after about 450 seconds which corresponds to flow passing through the entire domain about 3 times.” Comment: This is not usual; these simulations typically converge in around 30-60 seconds of simulated time.

80 Answer: This choice is made to be on the safe side. Otherwise, depending on what threshold is considered for “not changing considerably”, even a shorter period of time could be used. Nevertheless, this will not change the results considerably. We will present the time history of the power values for three mesh resolutions to clarify this further. In addition, we have changed the language to “Each case is run for 600 seconds where the results are calculated based on the average of the last 150 seconds corresponding to time series obtained after flow passing through the entire domain about 3 times. As can be seen in Fig. 4, the
85 power coefficients do not change considerably during this period.”

Comment: Fig 7 is referenced before 5 and 6. Please change the text or the order of the figures.

Answer: We have changed now the order of the figures.

“Based on our investigation, at 0.7 the axial velocity matches best with the one from ALM for OP as shown in Fig. 10.”
Comment: What is 0.7? Please clarify in the text.

90 Answer: This has been already mentioned in the text a few times for instance for 0.5 and 1 (lines 106 and 107). However, we clarify this further in the text. Moreover, we will show a few of these sampling locations such as 0, 0.5, 0.7, and 1 in Fig. 1 which is the sector illustration. For this case, “at 0.7” means the line with an azimuth equal to 70 percent of the sector angle after the sector beginning (location 0).

“4.2 Velocity Sampling Method” Comment: This section is again mixing the effects of velocity sampling with the vortex-
95 based correction.

Answer: In the beginning, we presented the results for this part without using tip/smearing correction for any of the considered cases. However, we changed them as they are now since we considered that maybe the reader is more interested in seeing the results with the preferred choice of the smearing correction. However, the conclusion drawn from these results does not change. We agree that it could cause confusion for the reader as they have not seen all the results. Therefore, we have revised this part and presented the results from cases without the smearing correction as you mentioned to avoid misunderstanding. Moreover, the figures are replaced accordingly and the reported error values are changed.

Fig 15 Comment: It is difficult to draw conclusions from these results. All the results differ, but which one is the correct one? The tangential force is different amongst all codes.

Answer: The conclusion drawn in this section for the choice of tip/smearing correction is based on the relative error compared to ALM presented in Fig. 16 and Fig. 18 in the submitted manuscript and Fig. 17 and Fig. 19 in the revised manuscript. It is clear that the relative error for the vortex-based correction has performed well near both hub and tip regions. Using Glauert or Shen correction has led to large error values near both hub and tip regions. As mentioned, the comparison is made relative to an ALM with vortex-based smearing correction as its performance has been validated previously (Meyer Forsting et al., 2019). Moreover, the y-label for Fig. 18 is wrong and it should be tangential relative error instead of axial for (a). This will be corrected in the revised manuscript.

“The mean relative errors for radial distribution of axial and tangential forces are 0.57% and 1.20% and the results are presented in Fig. 17 and Fig. 18.” Comment: This measurement is misleading, max error would be a better metric. The errors are quite large in some parts of the blade, especially towards the tip.

Answer: The reported error values are for the selected choice of vortex-based smearing correction which performs well all along the blade. We will however add the max error value to better clarify this. The large error values seen near hub and tip regions correspond to the Shen and Glauert tip corrections and this is why they have not been selected in the proposed model in the end.

2 RC2

Summary: The manuscript delves into various implementations of actuator sector models and compares them with actuator line results. The primary goal is to assess the accuracy and computational efficiency of the sector model compared to the line model. The paper demonstrates a good agreement between the actuator line and sector models, particularly in the rotor plane and wake flow. Notably, by employing the sector model, the authors achieved a remarkable 75% reduction in computational time compared to the actuator line model. This efficiency gain was made possible by using a larger time step without significantly compromising accuracy. Furthermore, the study highlights that reducing the time step for the actuator disk/sector does not offer a substantial advantage, given the associated increase in computational time. In conclusion, this manuscript provides valuable insights into the implementation and performance of actuator sector models in comparison to actuator line models. The findings shed light on how to achieve efficient yet accurate simulations in wind turbine modeling, which can be of great interest to researchers and engineers in the field of wind energy. Nevertheless, before this manuscript can be considered suitable

for publication, several issues need to be resolved. I have divided my comments into two categories: 'Major Concerns' and
130 'Minor Concerns'. The 'Major Concerns' pertain to conceptual and technical critiques requiring significant attention, while the
'Minor Concerns' draw attention to certain grammatical errors and typos.

1: The manuscript lacks clarity in presenting its novelty. Although it considers three key aspects: velocity sampling method,
tip correction, and time step, it is not evident how this work distinguishes itself from other peer papers in the field. The authors
should provide a more explicit explanation of the unique contributions of their study.

135 Answer: The main novelty of this work is that it presents the first comprehensive parametric study regarding the imple-
mentation of the actuator sector model and its effect on the results. Especially regarding the velocity sampling method and
tip/smearing correction, there is a knowledge gap in the literature. In most previous works, to the knowledge of the authors,
the choice of sampling method is not well justified and even the need for a more detailed study has been pointed out (Nathan
et al., 2015). In addition, other details such as the usage of the tip/smearing correction and rotor updating scheme are left out.
140 Moreover, previous works have often only considered a certain mesh resolution while this study has considered a wide range of
mesh resolutions to ensure the suggested velocity sampling method can perform well for all cases. Using the obtained results
in this study, it is evident how suggesting a velocity sampling method by using only one mesh resolution can lead to large error
values if the mesh resolution is changed. For instance, although sampling the velocities from the mid azimuth line of the sector
or locally results in relatively small relative error values for low-resolution mesh cases, the error values increase sharply as the
145 mesh is refined. In summary, the number of implementation details and a wide variety of considered cases in this study provide
the potential users with a robust implementation suggestion for the actuator sector model. This motivates those interested to
utilize this model for different applications and benefit from its computational saving with greater confidence. We will express
the novelty of this work more explicitly in the revised manuscript.

2: In Figure 3 (The illustration of the computational domain: Left: front-view slice at the rotor plane, Right: side-view at
150 the mid plane), it would be helpful to mark the location/position of the wind turbine in both figures for better clarity and
understanding.

Answer: We will add the location of the wind turbine in both figures. Moreover, there is a typo in the front view. The
diameters of the inner and outer refinement areas are 4 and 6 diameters, respectively. This will be also corrected in the revised
manuscript.

155 3: Finding all the simulations is challenging due to a lack of clear representation. It is suggested to add a table that compre-
hensively presents the changes made in the simulations, making it easier for readers to understand and follow.

Answer: We will add a table for each section where all simulations are presented along with changes that are made in
each of them. This includes the model used (ASM or ALM), velocity sampling method, rotor updating scheme, tip/smearing
correction, time step size, tip speed ratio, and mesh resolution. As the tables will occupy too much space for the main text, they
160 will be located in the appendix. The order of the tables is in such a way that minimizes the amount of blank space.

4: The conclusions heavily rely on the comparison between the ASM and ALM models. To strengthen the validity of the
ALM simulations, it is important to validate them against other benchmark cases.

Answer: The used ALM implementation and turbine is among the most widely used models in the literature (Asmuth et al., 2021; Martínez-Tossas et al., 2018; Fleming et al., 2015; Churchfield et al., 2012). The code is developed by the National Renewable Energy Laboratory (NREL) and is publicly accessible. In addition, the results from this ALM implementation have been previously compared with measurement and a good agreement was achieved (Nathan et al., 2017). Moreover, using BEM has been shown to produce satisfactory results compared to more sophisticated methods in uniform inflow similar to the case considered in this paper (Madsen et al., 2012). Therefore the results of ALM have been compared to BEM as a reference in Fig. 2 where a good agreement is shown. Hence, we believe that this should be sufficient to use ALM results for comparison, and adding a new section to validate the ALM results is beyond the scope of this work. We will add the reasoning stated here to the revised manuscript to justify why ALM results can be used for comparison. However, we ask the handling associate editor to inform us whether further validation is needed.

5: The section 4.2.2 New Position Approach is confusing and lacks sufficient explanation. The authors should provide further details on this approach to clarify its meaning and purpose.

Answer: The updating scheme for the rotor state is explained and the reason why it has been considered in this study is presented in lines 85-100 (section 2: Model description). We will add a cross-reference in the text to enhance readability. We have changed the language in the revised manuscript in such a way that it is more clear. We preferred to not mention this again to avoid repetition. However, if it is needed, we would gladly add a summary at the beginning of this section. Moreover, we have added, that since only the results from ASM with NP approach where the velocities are sampled at the sector beginning are comparable to NP-ALM, and since this is equivalent to sampling the velocities at the sector's end with OP approach, one could argue that the comparison should be made with OP-ALM. Despite this, we keep the results for the sake of completeness and to adhere to the progression of our investigation, i.e. we did not know from the beginning that this would be the case. The alternative would be to compare the ASM-OP results with both ALM-OP and ALM-NP results. However, we believe that it would be confusing and hard to follow for the reader. In addition, in "Model description" section, we have reformulated the language so it becomes more clear.

6: Page 19 mentions the use of load distributions from the BEM method with a Prandtl tip correction for comparisons. It is not clear whether the BEM data was obtained from their paper or calculated independently. If calculated by the authors, additional information is needed to better understand the process.

Answer: The BEM data is implemented and calculated by the author following the description in Hansen (2008) using the blade geometry and airfoil properties for NREL5MW turbine. It uses a Prandtl's tip correction to account for the finite number of blades and an empirical correction for the tip loss factor by Glauert for induction factors greater than 0.4. This will be added to the revised manuscript.

7: On Page 14, Figure 15, the paper includes two benchmark cases, BEM and ALM. It needs to be specified which one will be used to evaluate the performance of the ALS model.

Answer: The basis of the evaluation is the comparison with ALM results as shown in Fig. 16 and Fig. 18. The error values reported in the text are based on ALM results as it is mentioned in the text. Moreover, both in the caption and the axis labels for these figures, it is mentioned that the error values are reported compared to ALM.

8: In section 4.3 Tip/Smearing Correction Method, three smearing corrections are used. More detailed information about these three different methods is needed to ensure better clarity and understanding.

200 Answer: We will address this comment by providing a description of the used methods at the beginning of the section. Moreover, reviewing the submitted manuscript, an error was found in the presentation of the results from Shen tip correction. Therefore, the figures and results in this section will be updated in the revised manuscript. The conclusion however will not change as the vortex-based tip correction still shows a better agreement. The description will be similar to the following but more concise.

205 From a physical perspective, the calculated forces at the blade tip should be zero for a rotor with a finite number of blades as the flow from the pressure and suction sides meet. However, performing BEM calculations without tip corrections results in non-zero values for axial velocity and forces at the blade tip due to the assumption of infinite blades. Both Glauert and Shen tip corrections are intended to account for the finite number of blades in a rotor when performing BEM calculations Shen et al. (2005); Glauert (1935).

210 To address this, Glauert integrated a correction in BEM calculations to correct the induction velocity in momentum equations while Shen interpreted the correction to be done on airfoil data. The resulting correction is then multiplied by the calculated C_l and C_d values which are the lift and drag coefficients, respectively. This correction should satisfy two criteria. Firstly, it needs to tend to zero when approaching the tip and secondly, it needs to be 1 for a rotor with an infinite number of blades. The resulting equation for both of these corrections is presented as eq. 1.

$$215 \quad F_{tip} = \frac{2}{\pi} \times \text{acos}\left(\exp\left(-g \times \frac{B(R-r)}{2R\sin\phi}\right)\right) \quad (1)$$

where F is the tip loss factor, g is a constant, R is the blade radius, r is the radius at the blade location, and ϕ is the angle between the local relative velocity and the rotor plane. The difference between Glauert and Shen corrections is the value of constant g where Glauert used a value of 1 while Shen concluded that this constant is, among others, dependent on the number of blades and tip speed ratio and suggested the eq. 2 for determining its value.

$$220 \quad g = \exp(c_1 \times (B\lambda - c_2)) + 0.1 \quad (2)$$

where λ is the tip speed ratio. Using the measured data from two different turbines, values of -0.125 and 21 were found for c_1 and c_2 , respectively. The 0.1 is added to ensure the formulation does not fall apart for extremely large values of tip speed ratio. Another source of difference is in the implementation of SOWFA for Glauert correction. As the turbine hub is not modeled, it can be argued that a correction is needed also for the root of the blades. Therefore, similar to eq. 1, a root loss factor
 225 is calculated where $(R-r)$ is replaced with $(r-R_{hub})$ with R_{hub} being the hub radius. In the end, for each blade section, the total loss factor is calculated as eq. 3.

$$F_{total} = F_{tip} \times F_{root} \quad (3)$$

Although both of these corrections are meant for BEM calculations, it is common to use them to correct the forces obtained from Navier-Stokes solvers integrated with ADM and ALM due to its simplicity and low computational cost (Martinez et al., 2012; Asmuth et al., 2021). Therefore, they have been also considered here.

The vortex-based smearing correction considered in this study is however of another nature. Dağ and Sørensen (2020) showed that smearing the blade forces in the CFD domain to avoid numerical instabilities when using ALM results in the presence of a viscous core in the released vorticity. This reduces the induction at the blade location thereby overestimating the angle of attack and the calculated blade forces, especially near the blade root and tip where a large gradient for loads is present. Therefore, Meyer Forsting et al. (2019) presented a correction for ALM where a near wake model is combined with a viscous core model to calculate the missing induction. The results showed that the suggested smearing correction can resolve this issue for a wide range of operational conditions.

In this work, the implementation of this vortex-based smearing correction, publicly available in Meyer Forsting et al. (2019) and originally written in FORTRAN, is translated into C++ and is used along the SOWFA solver for ALM and the developed ASM by the authors to investigate whether it can correct the loading for the proposed ASM.

9: Figure 16 requires a benchmark case for easy comparison, either BEM or the ALM results should be included.

Answer: Figure 16 shows the relative error compared to ALM. Therefore, this is already included. Moreover, the results from BEM and ALM are included in Figure 15.

10: There are no figures for 4.4 Time-step Size. The authors should consider adding appropriate figures to support the discussion in this section.

Answer: Figures 19 and 20 (in the submitted manuscript) are the relevant figures for this section and they are both cited in the text. In the revised manuscript, we put both figures next to each other to increase the readability and save space.

11: On pages 18-19, Figure 22 shows the TKE profile along the streamwise direction, but it would be beneficial to include a figure showing the streamwise velocity for better context and comparison.

Answer: Originally, there was also a figure for stream-wise velocity included in this section. However, as the curves were similar, any comparison would be too difficult. Therefore, it was taken away. We will add one figure for the stream-wise velocity in the revised manuscript and will mention the similarity between the different models.

3 Final words

We would like to thank the referees and the editorial team again. We did our best to address the received comments. We kindly ask you to inform us about any further required changes and clarifications if necessary.

Kind Regards,

The authors

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