Response to Reviewer's Comments concerning wes-2020-107

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We would like to thank the reviewer for careful and thorough reading of this paper. Our response follows.

Referee #1 Comments

General:

Comment: The authors present results form a simplified model for use of transition prediction for wind turbine rotors. This topic is of considerable current interest not only to develop more adapted aerodynamic profiles to increase aerodynamic efficiency but also from a more scientific point of view to detect to main mechanism for transition from the laminar to turbulent state. However, it is no always easy to follow the text. Authors should consider:

- a) A list/table of abbreviations,
- b) Improving the style of writing by careful discussion with a native speaker,
- c) Being more exact in the wording,
- d) Shortening the text.
- e) Include references from recent experiments: (10.5194/wes-5-1487-2020, 10.3390/en12112102)

Answer:

- a) The authors agree that a table with abbreviations would make it easier for the reader to follow the text. We have included this feature as Table 3 at the beginning of the Results section (Section 4.1) in the revised document.
- b), c), and d) The style of writing has been improved. The manuscript has been revised to make the text exact and concise.
- e) The authors appreciate the suggestion from the referee. The mentioned references have been added to the list of literature and can be seen in the second paragraph of the Introduction section as well as in other parts of the revised document.

Specific:

- **Comment:** Title: what is meant by "Low order"? Order in what? What about "A simplified . . . "
  Answer: We understand that the use of the wording "Low-order modelling ... " in the title may confuse. We have changed it to "A simplified model ... ", as suggested by the referee since this is the intended meaning.
- **Comment:** Line 1: "onset ..." Do you mean the "critical" point, where damping becomes negative first? Or do you mean "start of fully turbulent" region by choice of N?
  Answer: "Onset of transition" is used meaning the position where the first turbulent spots

appear. This is supposed to happen at the location where the N factor reaches a critical value (9 in the current case). This has been made clear in the first paragraph of Section 4.5 of the revised version: "The onset of transition is assumed to occur when the amplification factor N based on the integral disturbance energy reaches N_{crit}. This state corresponds to the appearance of the first turbulent spots."

- **Comment:** Line 14. "reasonable accuracy" is not a scientific term. Use: accuracy in numbers instead, pp% for example
Answer: The authors agree that a more appropriate expression should be used to denote the accuracy of the model. The model is accurate (compared to the RANS results) to predict the chordwise velocity profiles and, for regions not too close to the root of the blade and stagnation point, also the spanwise velocity profiles. Concerning the transition locations, it is not possible to state the accuracy, since the PSE analysis of the RANS base-flow, which would be the numerical reference for comparison of transition locations, does not yield reliable results (we believe that this is because the mean-flow derivatives computed in the post-processing step are not smooth enough). Thus we have opted to change the sentence in the Abstract of the revised document to: "The BL model allows an accurate prediction of the chordwise velocity profiles. Further, for regions not too close to the stagnation point and root of the blade, profiles of the spanwise velocity agree with those from Reynolds-averaged Navier-Stokes (RANS) simulations." We have also added to the Abstract the sentence: "The developed method, which accounts for these effects, predicted an earlier transition onsets in this region (e.g. 19 % earlier than RANS at 26 % of the radius for the constant-airfoil geometry) and shows that transition may occur via oblique modes."

- **Comment:** Line 21: typo
Answer: "aerodynamiscists" has been corrected to "aerodynamicists"

- **Comment:** Line 66 to 69: "However, ... is expected to be more accurate ..." Why?
Answer: The integral boundary-layer equations require closure relations which are found through empirical relations [4]. Therefore, we believe the differential form of the boundary-layer equations delivers a more accurate solution. We have changed the text in the first paragraph of Section 2.1.1 of the revised article to: "However, a differential formulation is expected to be more accurate than its integral counterpart because the latter requires closure relations which are found through empirical relations [4]. For this reason, a differential formulation is selected in the present case."

- **Comment:** Line 85: Usually, when using body-fitted coordinates, a metric TENSOR appears (gij). Please show its relation the metric VECTOR you are using.
Answer: Here, we are using an orthogonal curvilinear coordinate system. Therefore, the metric tensor is represented as the Lamé coefficients h_i (Eq. 5), where $h_i^2 = g_{ii}$. Note that since the coordinate system is orthogonal $g_{ij} = 0$ for $j \neq i$. This has been clarified in the second paragraph of Section 2.1.1 of the revised version: "Moreover, ρ, p, and T denote density, pressure, and temperature, whereas $\mathbf{u}$ and $\mathbf{\Omega}$ represent velocity and rotation, respectively. h_i are the Lamé coefficients, where $h_i^2 = g_{ii}$ and g_{ij} is the metric tensor. Note that since the coordinate system is orthogonal $g_{ij} = 0$ for $j \neq i$."

- **Comment:** Line 96: "costly" Are we talking about € or $? Please be more accurate in wording and comparing typical amount of CPU hrs.
Answer: Costly here is referring to the number of CPU hours. We have not performed a comparison between the computational cost of a 2D and a 3D BL code mainly because, from the authors' experience, the 2D version yields more accurate results. However, we estimate that the computational cost of solving the 3D BL equations in terms of CPU hours (for a serial code) and memory should scale with the number of grid points in the spanwise direction. This point has been clarified in the first paragraph of Section 2.1.2 of the revised article to: "A 3D discretization can result in a solution procedure that is costly in terms of computational capacity and CPU time."

- **Comment:** Line 228: please give of precise definition of intermittency (γ)
Answer: γ is defined as

$$\gamma = 1 - \exp\left\{-(x - x_{tr})^2 \left(\frac{U_{e,tr}}{\nu}\right)^2 \hat{n}\sigma\right\}, \text{ for } x \geq x_{tr}, \tag{1}$$

where x is the chordwise position (measured from the stagnation line, x_{tr} is the chordwise position of the transition onset, ν is the kinematic viscosity, σ is the spot propagation rate, $\hat{n}$ is the nondimensional spot formation rate, and $U_{e,tr}$ is the edge velocity at the chordwise position of the transition onset [6]. For laminar flow, i.e., $x < x_{tr}$, $\gamma = 0$, and for fully turbulent flow, $\gamma = 1$. This definition has been included in the first paragraph of Section 4 of the revised document.

- **Comment:** Table 2: Geometry 2: "Varying" is not sufficient. Please state at least names.
Answer: Geometry 2 corresponds to the blade of the DTU 10 MW Reference Wind Turbine [1]. The FFA-W3-241 airfoil was used from 2/3 of the radius to the tip of the blade. From 2/3 of the radius to the root, the thickness of the mentioned airfoil was increased. This information has been included in Table 2 of Section 4.1 of the revised document.

- **Comment:** Line 268/269: "The discrepancies ... non-respect ... these locations." This sentence is hard to understand. Please improve.
Answer: We have changed the sentence in the second paragraph of Section 4.3 to: "The differences between the EVM and RANS results are larger at the inner radial position and close to the stagnation point. The reason is that the approximation for the spanwise pressure gradient given by Eq. (12) is more accurate at large radii and chordwise positions. This approximation relies on the assumption of C_p being constant over conical lines, which may not be respected at the mentioned locations due to the strong variation of the geometry in the radial direction and the flow three-dimensionality."

- **Comment:** Line 337: N = 9. Why did you choose this very specific value more appropriate for WIND TUNNEL experiments? As you may know, wind turbines operate in very different inflow conditions. Please improve.
Answer: We agree with the referee that $N = 9$ represents transition in an environment with very low turbulence intensity (0.07 % according to Mack's relation [5]), not representative of all atmospheric conditions. This value was selected in order to have a larger region of laminar flow in the RANS results, allowing a more detailed comparison between transition results from the developed model and RANS. This information has been included in the first paragraph of Section 4.5 of the revised article: "Although not representative of all atmospheric conditions, it is assumed $N_{crit} = 9$ in the current work to have a larger region of laminar flow in the RANS results, allowing a more detailed comparison between the developed model and RANS."

- **Comment:** Line 340: I do not understand why "γ=0.01" should correspond to N=9. Please explain.
Answer: The transition method in the EllipSys3D RANS code is based on the e^N model of Drela & Giles [2]. When the N factor reaches a critical value (9 in the current case), it is assumed that the flow starts transitioning to turbulent. At that location, the turbulence production term in RANS is turned on. This term is multiplied by γ whose value increases from zero to one along the chord following a given relation. The value of γ is a function of the chord and span location and is a result of the RANS simulations. The transition point at each spanwise section corresponds to the point where γ first deviates from zero. To extract the location of transition from the RANS data, we need to find those points. Due to the limited resolution in RANS simulations, we have selected location of $\gamma = 0.01$ to be the first point its value deviates from zero (the transition point). The following information has been included in the first paragraph of Section 4.5 of the revised article: " In the EllipSys3D code, when the e^N method of [2] indicates that N_{crit} was reached, the onset of transition is detected and the intermittency factor γ starts to grow from zero in the laminar region to one in the fully turbulent flow [7]. As the transition location is not directly stored in RANS data, we choose to select a small value for this parameter ($\gamma = 0.01$ is

selected) to indicate the transition location."

- **Comment:** Line 355 ff and Fig. 11: I do not understand your explanation why PSEX/PSER group on one side and PSER 2D/RANS group on the other deviate so much. Instead of a description only, give more possible physical reasons.
Answer: We have found an error in the code which prints the transition locations from the RANS and PSER 2D approaches. In the revised results, the agreement between these two methods is better, and they are closer to the PSEX and PSER results. The corrected results have been included in the revised manuscript and can be seen in Fig. (1).

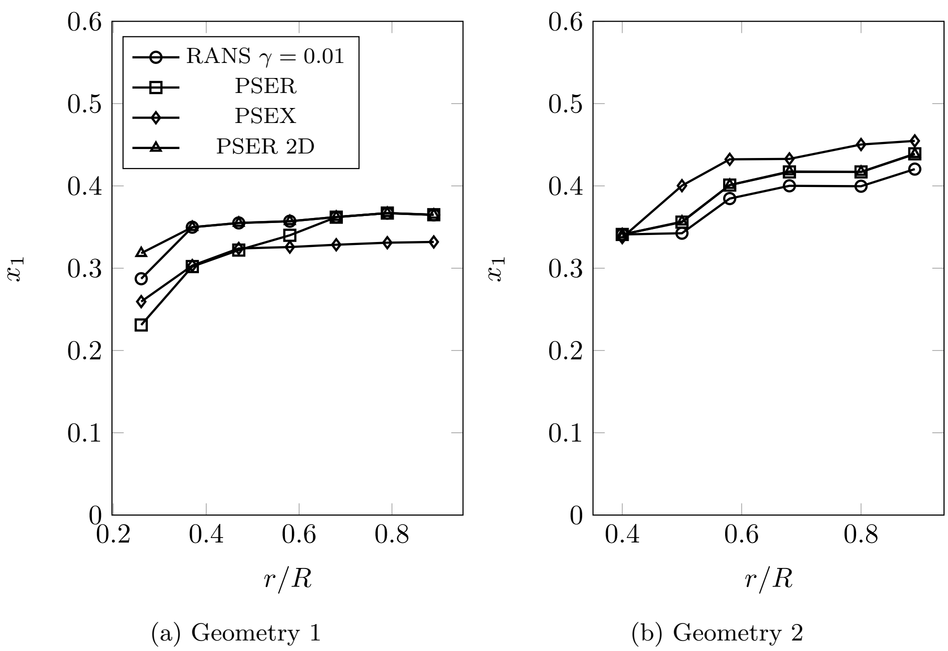

Figure 1: Transition locations.

- **Comment:** Line 389 ff and Fig. 15: I'm not sure if I have fully understood your explanation., If you are changing ω (!) only by a factor of 3, tip-speed-ratio and angles of attack may vary as well that strong, so that your blade fully falls out of a meaningful operating range. On the other side transition location "only" varies by a factor less that two. Please explain in more detail.
Answer: We agree that if the blade operates optimally at a rotation speed ω_{opt}, which is the rotation speed in the RANS computations, then $0.5 \times \omega_{opt}$ and $1.5 \times \omega_{opt}$ are not in the (normal) operating range of the blade. We selected those ω to force the effects of the rotation speed variation on transition to be more pronounced since transition seemed not to depend strongly on ω for the studied cases. The selected rotation speeds may also occur in a transient way, such as during the accelerating phase of the wind turbine. We adopted the approach of Du and Selig [3] of keeping the angle of attack constant while changing the rotation speed. This was done to segregate the effects of the variation of the spanwise velocity as well as Coriolis and centrifugal forces from those caused by the variation of the angle of attack. For this reason, the transition locations vary less than ω. These points have been made clearer in the fifth paragraph of Section 4.4 of the revised document: "The effects of rotation on the spanwise velocity are investigated using the approach of Du and Selig [3], in which the rotation speed is varied while the angle of attack is kept constant. This allows for segregating the effects of the variation of the spanwise velocity as well as Coriolis and centrifugal forces from those caused by the variation of the angle of attack."

- **Comment:** Line 392: "accelerates transition". I think "accelerate" is not the right expression. What about "shifts the transition location closer to the nose"?
Answer: The authors are thankful for the suggestion and have changed the sentence in the eighth paragraph of Section 4.5 of the revised document to "The trend shown in the picture

indicates that the increase in the rotation speed shifts the transition location closer to the nose."

- **Comment:** Line 457: "reliable estimate". Again, please state accuracy of your model more quantitatively
  Answer: We have changed the sentence in the second paragraph of the Conclusions of the revised document in the same way as stated in the answer to "Comment: Line 14...".

References

[1] C. Bak et al. "Light Rotor: The 10-MW reference wind turbine". In: *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition*. 2012.

[2] M. Drela and M. B. Giles. "Viscous-Inviscid Analysis of Transonic and Low Reynolds Number Airfoils A Theory for Predicting the Turbulent-Spot Production Rate". In: *AIAA Journal* 25.10 (1987), pp. 1347–1355. DOI: 10.2514/3.9789.

[3] Z. Du and M. S. Selig. "The effect of rotation on the boundary layer of a wind turbine blade". In: *RENEW ENERG* 20 (2000), pp. 167–181. DOI: 10.1016/S0960-1481(99)00109-3.

[4] A. van Garrel. *Integral Boundary Layer Methods for Wind Turbine Aerodynamics - A Literature Survey*. Technical report ECN-C–04-004. Energy Research Centre of the Netherlands, 2004.

[5] L. M. Mack. *Transition prediction and linear stability theory*. Technical report AGARD-CP-224. AGARD, 1977.

[6] R. E. Mayle. "A Theory for Predicting the Turbulent-Spot Production Rate". In: *Journal of Turbomachinery* 121.3 (1999), pp. 588–593. DOI: 10.1115/1.2841356.

[7] Ö. S. Özçakmak et al. "Laminar-turbulent transition characteristics of a 3-D wind turbine rotor blade based on experiments and computations". In: *Wind Energy Science* 5.4 (2020), pp. 1487–1505. DOI: 10.5194/wes-5-1487-2020. URL: https://wes.copernicus.org/articles/5/1487/2020/.