Reply to the comment of anonymous referee number 2

The authors want to thank the referee very much for his detailed comment.

The authors feel that there are major misunderstandings, probably caused by the introduction of the original paper, which was not clear enough or even misguiding (a draft for a new introduction is appended to this letter of response).

Many of the reviewer's comments aim on the reliability of the CFD solution. The authors have attempted to make clear in the introduction of the paper (and were obviously not very successful with this attempt) that they consider their work as a contribution to model updating, or reduced-order modelling, in the sense that they try to update a fast engineering model (BEM) with data from an expensive high-fidelity method (RANS, in this case). The data transferred from RANS to BEM are the 3D rotor polars. Two different (existing) methods for the extraction of 3D rotor polars from CFD solutions are investigated. Subsequently, the 3D rotor polars are applied in BEM simulations. The procedure is successful if the BEM with 3D rotor polars produces similar results as the RANS simulations (this is verification for the operating points at which the polars were extracted, and code-to-code validation for different operating points). In this context, it is not necessary that the CFD solution is very accurate (in the sense of "close to reality"). We assume (without proving it) that our RANS solution is more reliable (closer to "the truth") than the BEM with common 2D airfoil coefficients and empirical corrections. When applying the method, it is of course desirable to use a thoroughly validated RANS setup and solution (although obviously no CFD simulation will ever be "the truth"), but the validation of the CFD simulation is a complex task for itself and therefore not in the scope of the proposed paper. The authors will make this clearer by extending and rewriting the corresponding paragraph (p. 2, l. 11ff) in the revised version of the paper (see the appendix of this letter of response).

Furthermore, it is very important to note that the methodology of BEM with 3D rotor polars is not suitable for blade design, because the 3D rotor polars depend on (and are possibly very specific to) the geometry of the rotor blade. This has always been conscious to the authors, but it has not been properly documented in the proposed paper. The applications which the authors had in mind are simulations in a later design stage, where a (preliminary) geometry is already fixed and a large number of load simulations is required, for example in the certification process. Only in this stage, it is worth the effort to create a RANS setup, perform RANS simulations and obtain a CFD-based, but very fast aerodynamic model (BEM with 3D rotor polars) which can be applied in a large number of simulations. This important explanation is missing in the original version of the paper. The introduction will be rewritten in the revised version of the paper in order to clarify this (see appendix).

In the following, the authors have split the reviewer's comment in several items and responded to every single item. The original reviewers comment is reproduced in *blue italic* letters.

Numbering in square brackets at the beginning of each paragraph has been added by the authors.

[1] This paper is very relevant because it discusses the validity of the widely used BEM model and its input. Polars have been extracted from 3D CFD computations and compared to 2D polars

from e.g. 2D CFD computations. However, some important information is missing. We need to know whether the solver includes free transition and how big the CFD domain is.

In the RANS simulation, the flow is fully turbulent, so there is no transition modelling included. The CFD domain (mesh) has the shape of a cylinder with a radius of 6 *R* and an axial extension from 4 *R* upstream to 10 *R* downstream of the rotor, where *R* is the radius of the rotor. These pieces of information will be added to section "3.2 RANS setup" of the paper.

[2] Furthermore, it is assumed that the 3D CFD computations are correct and represents the "truth". Couldn't this be questioned? My experience is that (3D) CFD does not capture stall correctly. So do we believe in the stations where we have separated flow?

As noted in the introduction to the original paper (p.2, l. 11ff), and as explained in more detail at the beginning of this letter of response, our objective is to do a kind of model updating / reduced order modelling. The intention is to use 3D rotor polars in BEM in order to obtain within seconds a result which is similar to a result from CFD which would require many hours or days to be obtained. A realistic (and validated) CFD solution is very desirable and definitely essential for practical application of this method, but it is not required for the investigation of the methodology which is done in the proposed paper.

[3] And forces can be too high if the domain is too small and the flow has been pushed through the rotor because of the boundaries of the domain. The domain boundaries probably have to be 10 to 20 rotor diameters away.

Please see the response to [1] for the distance of the boundaries of the CFD domain. Simulations with a larger domain did not show significant differences. The forces from our RANS simulations are in the correct order of magnitude (please also see the response to [5]). Anyway, as explained above, an accurate RANS solution (in the sense of "close to reality") is not required for the investigation within the proposed paper.

[4] Furthermore, the extraction of the data can also be questioned. Was the radial component extracted?

The radial velocity can be extracted, but it is not used in the proposed paper. Please see the response on [18] for a more detailed statement.

[5] Also, there is something with the values where force distributions are shown. They are about 10 times too high if the forces are Newton per meter.

As the axis labels indicate, the forces are in Newton, not in Newton per meter. This is suitable in this case as we use blade elements of equal length. The length of the blade elements is 2.87833 meters (rotor radius 89.15 m minus hub radius 2.8 m, divided by 30 (number of blade elements)). We consider changing the plots to N/m in order to avoid confusion.

[6] Finally, the conclusions are not really conclusions but self-fulfilling statements since it is obvious that data based on 3D CFD compares better to 3D CFD.

Please see the responses to [19] and [20] for statements on the conclusions.

[7] Since the overall aim of our research is to provide data and methods for the further development of wind turbines, we have to wear the perspective of the wind turbine manufacturers. Would I as a manufacturer blindly believe the 3D CFD computations? I think not.

Neither would the authors blindly believe in CFD computations (and not in BEM, vortex wake or any other type of simulation either). Validation of CFD simulations (by experimental data) is a task of outstanding importance. It requires the availability of suitable experimental data, and it is quite a large effort. This task is too large to fit into the projects on which the authors are currently working. In the context of the proposed paper, it is not necessary to show the validity of the CFD simulations. All methods in the paper can be applied to any CFD simulation, no matter whether they are believed to be valid or not. The intention of the proposed paper is (only) to investigate methods for the transfer of information from high-fidelity simulations (RANS) to fast engineering models (BEM) in the sense of model updating.

[8] Therefore, I do not think that the advice should be to extract polars directly from 3D CFD. However, I think it could be more interesting to discuss why we see these differences between 2D and 3D.

The authors completely agree that an in-depth analysis of the causes for the deviations would be very interesting. For the proposed paper, however, the focus is on model updating / reduced-order modelling, i.e. enhancing (or updating) a fast engineering method (BEM) by data from an expensive high-fidelity simulations (RANS). For this reason, in the paper we only say very roughly that the differences are due to 3D effects (tip or hub vortex, centrifugal forces, downwash, 3D induction distribution, etc.). A detailed investigation of the causes for the difference between BEM-2D and BEM-3D (or RANS) is not the purpose of the paper. For such an analysis, it would be better to do a thorough validation of the CFD result first (in particular at the critical positions, such as the inboard region where the flow is partly separated and heavily three-dimensional). However, this is outside of the scope of the proposed paper.

As there are several published methods for the extraction of the angle of attack from CFD results, their application for creating 3D rotor polars and using them in a BEM analysis is quite a logical consequence. To the authors' knowledge, there is hardly any literature where not only the extraction of 3D rotor polars, but also their application is investigated. With the proposed paper, the authors might contribute to close this gap in current literature. The analysis in the proposed paper shows that the application of 3D rotor polars can in principle work very well, but that it also brings several difficulties, as for example the pitch angle dependency of the polars. The authors are not conscious of a publication where this has been described before, and they believe that such findings deserve publication to the wind energy community.

[9] Why do we see this AOA shift for different pitch angles? I am left with the feeling that you (and we) are overlooking something. How do we interpret the abstraction of AOA in 3D flow?

We are not sure how you mean "interpret the abstraction of AOA in 3D flow", but in the context of this work, the AoA is calculated using the induction factors in the manner of the BEM (equations (5) and (6) in the paper), and the induction factors are obtained from the annular sections method or the inverse BEM method. This could be considered a local 2D-equivalent AoA, based on the induction factors from 3D CFD, but dependent on the method for extraction of the induction factors. We do not have a simple explanation for the pitch angle dependent shift in the polars, except for the vague statement that it has to do with different induction (magnitude and distribution) for different pitch angles, and hence different 3D influence (e.g. crossflows and rotational augmentation close to the hub, where we have the largest shift). See also the response to [21].

[10] I propose the following should be considered in the paper:
** look into the values of the forces, where I think there is an error*
** describe the CFD setup in more details (domain size, free transition etc) and*
** analyse where we see differences to 2D data and why you observe the shifts in angle-of-attack*
** change the conclusions so that it is not self-fulfilling statements.*

The values of the forces are correct, in particular their order of magnitude, cf. response to [5]. Some words on the CFD setup will be added (cf. response to [1]). We will see if we can find some more explanations for the differences between 3D and 2D airfoil data as well as the pitch angle dependency (although the investigation of the reasons is not the main aspect of this paper) and we will consider revising the conclusion (cf. response to [19] and [20]) in order to avoid what you call self-fulfilling statements.

[11] I do not think that you should propose to use polars extracted directly from 3D CFD, because you then make the assumption that 3D CFD is correct.

As for any simulation, the results obtained with this method need to be critically reviewed and – if possible – validated by comparison with appropriate experimental data. If you use common BEM with 2D airfoil coefficients, then you are assuming that BEM with 2D airfoil coefficients is correct. Validation is always required, whether using 3D rotor polars or not, but it is not the subject of the proposed paper. In the proposed paper, the focus is on model updating, i.e. bringing the BEM results close to the RANS results by using information from RANS. Please also see the responses to [2] and [7].

[12] Specific comments
Abstract Line 8: "the the"

This will be corrected, thanks.

*[13] Chapter "Introduction" * I think you are missing one of the first attempts to make such airfoil characteristics from CFD: – Bak, C., Fuglsang, P., Sørensen, N. N., Aagaard Madsen,*

H., Shen, W. Z., & Sørensen, J. N. (1999). Airfoil characteristics for wind turbines. (Denmark. Forskningscenter Risoe. Risoe-R; No. 1065(EN)).

Thanks for the remark; a reference was added to the introduction for the sake of completeness (see new introduction in the appendix).

[14] Section “Inverse BEM” Last sentence: I do not really understand

Assuming that you mean the sentence “There is no need to do a post-processing of the volume solution of the RANS, as there is in the annular sections method for the calculation of the averaged axial and tangential velocities.” (p. 6 l. 19f): This is a rather technical remark. There are CFD solvers (like TAU) which can output the solution on the surfaces of the domain (surface solution) separate from the solution on the whole grid (volume solution). The surface solution does not contain many points and is therefore quite a small file which is easy and fast to handle. The volume solution, in contrast, can have a file size of many Gigabytes and it may take some time and need some resources to copy, read and post-process such files. The inverse BEM requires as input only the forces on the surface, which are contained in the surface solution file, whereas the annular sections method requires a post-processing of the volume solution file, which is a bit less convenient. We will clarify or delete this sentence in the revised version in order to avoid confusion.

[15] Section “RANS setup” How big is the domain? How far upstream? Downstream? And in radial direction? If the domain is small this can influence the result

Please see the response to [1]. The proposed paper does not have the intention to discuss the validity of the CFD results, cf. the detailed explanation at the beginning of this letter of response.

[16] Section “Influence of pitch angle” Figure 5: Title of plot is not clear.

We forgot to update the title of the plots after removing the 20 deg polars (for the sake of clarity; with the 20 deg polars there are too many symbols and lines). We will correct the title, e.g. “Comparison of the Cl values obtained at pitch 0° and 10°”.

[17] Section “Comparison between Rans, …” Fig 7: What does the forces represent? N/m? If so: An integration of the tangential forces result in a power delivered by the blade of around 30MW – and for 3 blade 90MW. Can this be right? A factor of 10? And the same is the case for the axial loading

The forces are in Newton (not normalized, cf. response to [5]) and for the whole rotor (i.e. multiplication by the number of blades is already done). The sum of the local axial forces in figure 7a (sum of the values at the dots) is around 1.82 MN (1.82e6 N), which appears to be a reasonable order of magnitude. This value matches with the values reported by different parties in a technical report / deliverable from the EU project AVATAR (cf. [Ref. 1] at the end of this letter of response, figures 22 and 23; note that in this report, according to the authors’ interpretation, a case with wind 11 m/s and rotation speed 8.836 RPM was simulated (cf. Table

2 in the AVATAR report) instead of 9.6 RPM in our paper, so the resulting global force in our figure 7a is larger than in the AVATAR report, but it is definitely in the same order of magnitude).

The sum of the local torque contributions (values of the dots in figure 7b times local radius and sum over all these values) is around 9.51 MNm. This value multiplied by the rotational frequency Omega = 1.00531 1/s leads to an aerodynamic power of around 9.6 MW, which seems to be realistic to the authors as the rated power of the turbine is 10 MW and the wind at this operating point (11 m/s) is still a bit below the rated wind speed (11.4 m/s).

[18] You extract axial and tangential induction. What about radial? Couldn't this explain some of the AOA shifts?? Or what explains the AOA shift for different pitch angles?

We are able to extract the local radial velocities, but we did not use them in the analysis. We are not sure how the reviewer would define a radial induction factor (specifically, which reference velocity should be used for its definition). Common BEM theory does not account for radial induction, and as we want to do a model update (i.e. tuning the fast model (BEM) with high-fidelity (RANS) data such that the result of the BEM gets closer to the RANS result), instead of inventing a new variant of BEM, we leave the BEM algorithm itself as it is, i.e. without accounting for radial induction. However, the comparison of the radial velocities between the different load cases for explanation of the pitch angle dependence seems to be interesting. We will make and attempt in this direction and maybe add some remarks on that in the revised version of the paper.

[19] Section "Conclusion"
** First finding: – It is obvious that polar data obtained from 3D CFD agrees better to 3D CFD than data not obtained from 3D CFD. So that is not really a conclusion. It have to be so – otherwise you have been inconsistent.*

The intention of this bullet point was to state that the polar extraction and BEM with 3D rotor polars has been applied successfully. This is pure verification of the implementation for the load cases which had been used for the extraction of the polars (of the cases shown in the paper, these are E1 to E3); however, this is more than pure verification for the load cases which had not been used for polar extraction (P1 to P3 in the paper). For cases P1 to P3, the comparison should be considered a code-to-code validation. The reviewer is right that this is not really a conclusion, but rather a part of the result. This first item should therefore not appear as a bullet point, but rather be included in the very brief summary paragraph at the beginning of section 5 "Summary and conclusions".

*[20] * Second finding: – This is also obvious because you use the inverse BEM. So this is not either a conclusion*

The authors think that this is actually worth mentioning. To our knowledge, there is so far no literature in which the application of 3D rotor polars obtained by different methods is investigated. For instance, in the work by Guntur and Sorensen (2014) (from TORQUE 2012), the annular sections / AAT method was used for determination of the angle of attack, but there was no subsequent application of the obtained 3D rotor polars in a BEM code, which is why the inconsistency of the annular sections method to the application in BEM was probably not found, or at least not reported in the publication by these authors. Therefore, we consider this to be a new finding and a contribution of the paper. In the beginning, we used only the annular sections method for obtaining the 3D rotor polars, and we were quite surprised by the offset in the forces which we saw in the results. The interesting aspect is rather not that the inverse BEM is consistent to the BEM, but that the annular sections / AAT method is not. It is possible that the inconsistency of the annular sections method to the BEM algorithm is obvious for some people, but we doubt that everyone will see this inconsistency at the very first glance, and it is (to our knowledge) not documented in literature so far.

*[21] * Third finding: – I would actually like to know WHY the polars change with pitch angle. Please consider a bit more.*

This is indeed a very interesting question, on which the authors do not have a simple answer. With a different pitch angle, we have different induction (less induction if the blades are pitched towards feather). This changes, more or less, all of the 3D effects on the blades (induction, crossflows, rotational augmentation, tip / hub vortices, …). In the context of BEM, all these 3D rotor effects have to be lumped together in one local angle of attack. This is quite a simple reduction for a number of rather complicated effects. Of course, these are only vague hypotheses which should be justified in a closer analysis. The authors think that this could be an opportunity for another publication after thorough investigation of the effects, but in the current paper, the focus should stay on updating the BEM with data from CFD simulations.

On behalf of the authors,

Marc S. Schneider

[Ref. 1] Niels N. Sørensen, Martin O.L. Hansen, Néstor Ramos García, Liesbeth Florentie, Koen Boorsma: *Power Curve Predictions WP2 Deliverable 2.3*, AVATAR, available online: http://www.eera-avatar.eu/fileadmin/mexnext/user/report-d2p3.pdf

Appendix: Proposal for new introduction (section 1) of the proposed paper, taking into account both reviewers' feedback

1 Introduction

The Blade Element Momentum method (BEM) is a widely used method for wind turbine design and load simulations. The BEM method intrinsically contains the assumption of radial independence of the blade elements, i.e. the blade elements do not influence each other, and 3D phenomena like the downwash from tip or hub vortices can only be captured by additional, mostly empirical submodels. BEM usually uses two-dimensional airfoil data, which were obtained for cross sections of the blade by wind tunnel experiments or numerical simulations. These 2D airfoil data, together with some empirical models, are assumed to completely describe the aerodynamic behaviour of each blade element.

In order to account for 3D influence in the BEM, various correction methods have been proposed: For a better description of the rotational augmentation of aerodynamic forces and delayed stall close the blade root, models for correction of 2D airfoil coefficients were developed e.g. by Du and Selig (1997), Chaviaropoulos and Hansen (2000) and Dowler and Schmitz (2014). For the decrease of aerodynamic forces close to the blade tip (tip loss), the traditional model by Prandtl/Glauert (described e.g. in Hansen (2008)) is still widely used, although improved and new tip loss models have been proposed (e.g. Shen et al. (2005) or Sørensen et al. (2016)). Bak et al. (2006) present a more general approach which corrects 2D airfoil data based on semi-empirical relations for the pressure distribution.

On the other hand, there are methods which avoid additional submodels, and instead try to include all the aerodynamic behavior into airfoil coefficients. In some works in the context of the NREL phase VI rotor, e.g. Tangler (2002), airfoil coefficients are evaluated based on data from rotor experiments as well as on 2D airfoil data.

As high-fidelity CFD simulations of whole rotors are not too difficult to obtain nowadays, it is quite an obvious idea to use data from 3D rotor CFD simulations in order to improve the results of a BEM analysis. The most straightforward way to achieve this is to calculate airfoil coefficients from CFD simulations, which can then be applied in a BEM code. This way of transfer from an expensive high-fidelity method to a fast engineering model, which we refer to as *model updating*, should enable the BEM to produce results which are very similar to CFD results for a range of parameters.

The objective of this work is to perform a model update for BEM by using airfoil coefficients from 3D rotor RANS simulations (these coefficients will be called *3D rotor polars*). This means that BEM is treated as a kind of reduced-order modelling, in the sense that it is attempted to reproduce results from RANS simulations by a drastically simpler and faster model. While validation of CFD results is of outmost importance if the results are meant to be used for productive purpose, a validated CFD solution is not necessarily required for investigation of the feasibility and the limitations of this model update. Therefore, the validation of the RANS solution is not addressed in this work. Instead, the results of the BEM with 3D rotor polars are validated against a number of RANS simulations in the sense of a code-to-code validation. The intended application of the BEM with 3D rotor polars are simulations in a later design stage, for instance in the certification process, when the geometry of the rotor is already fixed. BEM with 3D rotor polars is not suitable for blade design, as the airfoil coefficients extracted from 3D rotor simulations are specific to the blade geometry, and the feasibility of 3D rotor polars for different geometries than the one used in the RANS simulations is questionable and not investigated in the current paper.

Within this work, two methods for determination of a set of 3D rotor airfoil coefficients from a number of steady-state three-dimensional RANS simulations of a rotor are investigated and compared. This requires that the local angle of attack and the lift and drag coefficients are extracted from RANS solutions. The extraction of lift and drag coefficients and the corresponding angle of attack from CFD simulations by different methods has already been described e.g. by Bak et al. (1999), by Johansen and Sørensen (2004) or Guntur and Sørensen (2014). In the present work, two methods for the evaluation of the induction factors and the local angles of attack at the blade were tested and compared. The airfoil coefficients obtained by this procedure will be called *3D rotor polars,* and the BEM with 3D rotor polars will be referred to as *BEM-3D*, as opposed to BEM with common 2D airfoil coefficients, which is referred to as *BEM-2D*.

Most of the content of this paper has already been presented at "The Science of Making Torque from Wind" (TORQUE) 2016 in Munich (Schneider et al., 2016). In contrast to the original paper, the present work uses the more renowned reference wind turbine from the European project INNWIND.EU, developed at DTU, with a rotor diameter of about 178 meters and a rated power of 10 MW (cf. Bak et al. (2013)). In addition, section 4 contains some new material in which the difference between steady states is evaluated in order to assess the accuracy of the slope of the 3D rotor polars and their potential for application in unsteady BEM simulations.

New references (the others can be found in the original version of the paper):

J.L. Tangler: *The Nebulous Art of Using Wind-Tunnel Airfoil Data for Predicting Rotor Performance.* National Renewable Energy Laboratory, Golden, Colorado; AIAA 2002-0040

C. Bak, P. Fuglsang, N.N. Sørensen, H. Aagaard Madsen, W.Z. Shen, J.N. Sørensen (1999): *Airfoil characteristics for wind turbines*. Denmark. Forskningscenter Risoe. Risoe-R; Nr. 1065(EN)