Manuscript Title: Investigating Grease Behaviour in Tilted Double-Row Tapered Roller Bearing Installed in Wind Turbine by Developing a Full Scale Multi-Phase CFD Model

Journal: Wind Energy Science

Responses to Comments from Reviewer 2

Referee Comment:

Page 1: Abstract: Are the grease and air phases assumed to be incompressible throughout?

Author Response:

Thank you for pointing out this important clarification. Yes, both grease and air phases were assumed to be incompressible throughout the simulation. This assumption is justified as the flow velocities involved are significantly lower than the speed of sound, and high contact pressures are not considered in this study.

Accordingly, we have revised the manuscript to explicitly state this assumption.

Referee Comment:

Page 1: Introduction: The opening paragraph is not necessary in the overall scheme of the work? Go directly to the main work

Author Response:

Thank you for this suggestion. Based on your comments and those of the other reviewer, the introduction has been streamlined, focusing only on the essential elements needed to contextualize and describe the work.

Referee Comment:

Page 2: Introduction: the word "used to carry higher radial and axial loads…" needs to be quantified. This is beneficial to support the last statement in this paragraph which states "Therefore, double-row TRB are most commonly used as main bearing in wind turbines to support these high loads and provide better mechanical integrity".

Author Response:

Thank you for pointing out this inconsistency in the text. Unfortunately, due to industrial confidentiality, we are not allowed to disclose the specific values of the forces and moments that the bearing is designed to withstand. However, we have revised the text to broaden the discussion to include other bearing types and configurations.

In fact, using two tapered roller bearings (TRBs) mounted in O-arrangement or a double-row TRB leads to equivalent results. In this paper, the term double-row TRB is used because the outer races of the two bearings are manufactured as a single component, in order to minimize the number of parts and reduce axial space requirements.

It is worth noting that many turbines use two TRBs in O-arrangement instead of a double-row bearing, but this does not diminish the relevance of the study, since in many cases the lubrication of the two raceways is carried out using methods similar to those described here.

Referee Comment:

Page 2: Introduction: the statement uses it, redundantly by saying "It supports loads in multiple direction" ... the word "it" becomes unclear. Need to be more specific whether it refers to a double-row or single-row

Author Response:

The text has been revised accordingly, and we were consistently refered to the double-row TRB throughout the manuscript.

Referee Comment:

Page 2: Introduction: General comments. You write with no general quantification made for models comparison. Revisit this aspect. This is a general comment.

Author Response:

Thank you for your comment. Indeed, it is challenging to cite works similar to ours, as to the best of our knowledge, full CFD models of large-scale bearings such as main bearings in wind turbines have not been developed before.

In this respect, our model can be considered original. Nonetheless, we have reviewed the literature to support the quantitative values related to bearings, and tried to enrich the introduction by including this information.

It is also worth noting that the results presented in this paper are mainly qualitative in nature, especially regarding the grease distribution. The quantitative results, on the other hand, are presented in a novel manner.

Referee Comment:

Page 2: Introduction: A few statements are unclear, and paragraphs are general too wordy to arrive at a conclusion. For instance, the paragraph that started with "Eco-friendly and sustainable developments...", is too wordy. Reviewer was lost in the idea the paragraph sought to achieve.

Author Response:

As previously mentioned, the authors have revised the introduction both to provide a more practical and application-oriented context, and to avoid statements—such as the one highlighted—that add little technical value.

Referee Comment:

Page 2: Introduction: The reviewer strongly believes that the chosen operating conditions (grease fill ratios, tilt angle, rotational speed) need justification, cite industry standards or typical wind-turbine practice.

Author Response:

Thank you for pointing this out, as it helped the authors realize that an important objective of this study had not been clearly explained.

In fact, it is worth noting that the standard industrial practice followed by the company involved in this work—as well as by many others, is to completely fill the bearing with grease at the beginning of its service life. After an initial churning phase, part of the grease is expelled from the bearing, and the system stabilizes with a grease fill ratio between approximately 40% and 50%. This level is then maintained through periodic relubrication, since a small amount of grease may continue to escape past the seals over time. This is also why estimating the pressure on the seals becomes important.

Maintaining such a high grease fill ensures reliable lubrication, as it increases the likelihood that critical areas within the bearing will be reached. However, it also results in significant load-independent power losses which lead to energy inefficiency and increased operating temperatures.

Additionally, the more grease is present inside the bearing, the higher the risk of elevated pressure on the seals. While we cannot disclose specific pressure values due to industrial confidentiality, this is a relevant design concern.

This study therefore aims to explore the internal behaviour of the main bearing when the grease fill is reduced below the typical 40–50% range, to assess whether such a strategy could help save both material (grease) and energy (through reduced load-independent losses), while still ensuring reliability—i.e., sufficient lubrication and lower seal pressures.

This study is done in collaboration with the wind turbine manufacturer and these operating conditions were chosen in consultation with them.

These details have been included in the revised manuscript.

Referee Comment:

Page 3: Introduction: From Hoeprish (2005) the author needs to provide details on grease

type, fill ratio, and how grease-film thickness was measured.

Author Response:

These details have been added in the revised manuscript.

Referee Comment:

Page 3: Introduction: The introductory section is not properly concluded. A standard journal writing practice is to end with a “paper organization” paragraph that outlines the content of each subsequent section.

Author Response:

Thank you for pointing out this stylistic oversight. We have revised the introduction section by clearly identifying the objectives of the study and included a brief outline of the paper’s structure.

Referee Comment:

Page 4: CFD Model Development: The author must substantiate the use of a 0.98 scale

factor. This may not be the most appropriate method. Consider instead referencing a “0.68

mm gap between roller and raceway," as it directly links geometry to lubrication film thickness.

Author Response:

As mentioned above, film thickness is not the main focus of this study and is not something that can be accurately evaluated using a full-scale bearing model. That said, there is extensive literature supporting the use of a 0.98 scaling factor. It helps in the refining of mesh near the walls to avoid any triangular cells and to obtain better numerical accuracy.

Maccioni, L., Chernoray, V. G., and Concli, F.: Fluxes in a full-flooded lubricated tapered roller bearing: particle image velocimetry measurements and computational fluid dynamics simulations, Tribology International, 188, 108 824, https://doi.org/10.1016/j.triboint.2023.108824, 2023a.

Maccioni, L., Ruth, L., Koch, O., and Concli, F.: Load-Independent Power Losses of Fully Flooded Lubricated Tapered Roller Bearings: Numerical and Experimental Investigation of the Effect of Operating Temperature and Housing Wall Distances, Tribology Transactions, 66, 1078–1094, https://doi.org/10.1080/10402004.2023.2254957, 2023b.

This explanation has been added to the respective section in the revised manuscript.

Referee Comment:

Page 3: CFD Model Development: Clearly included the boundary conditions. This is a 360 degrees rotating model, so wondering how the BCs were imposed.

Author Response:

In the revised version of the paper, the type of boundary conditions and the values assigned to them have been summarized. Additionally, explanation has been added to better explain the meaning and role of the variables.

Referee Comment:

Page 4: CFD Model Development: Report key parameters and stats of the half sector mesh.

Author Response:

The key parameters of half sector mesh have been summarized in Table 2 in the revised manuscript.

Referee Comment:

Page 5: CFD Model Development: In addition, justify the hexahedra structure. Not just by providing figure. For instance, will the gird converge? You can report a quick text for instance, "We double the cell count in the film gap and observe < 2 % change in torque."

Author Response:

The authors conducted a preliminary mesh sensitivity study using a single-sector simulation under fully filled (single-phase) conditions. This approach was chosen because simulating the two-phase fluid case necessarily requires the full model, and its transient nature prevents convergence in less than 45 days of computation time—making it impractical for routine testing.

The preliminary study showed that increasing the number of cells by 50% compared to the mesh used in this work resulted in a variation in power losses of less than 5%. This provided a reasonable basis for defining the mesh size adopted in the study, although the assessment was carried out under simplified conditions.

Referee Comment:

Page 5: CFD Model Development: This is more of a technical question, but if storing 12.5 million points in MATLAB creates memory issues, explain how it was achieved. Did you use a cluster model? If so, document RAM usage and runtime of the MATLAB script for the 12.5Mcell mesh.

Author Response:

A MATLAB routine was used to calculate the main coordinates of the blocks of the entire bearing and converting it into compatible format. These blocks were then used in conjunction with blockMesh to generate the final mesh. In OpenFoam, while creating the mesh, only the coordinates of the vertices should be written in blockMeshDict file. These coordinates are much lesser than the number of cells.

Referee Comment:

Page 6,7&8: CFD Model Development: So many details are written as if the reader is an expert user of OpenFOAM. So, free the journal of jargons.

Author Response:

In the revised version of the paper, the authors have provided explanations of the meanings of the various common terms used in OpenFOAM.

OpenFOAM Foundation: OpenFOAM: The Open Source CFD Toolbox, OpenFOAM Foundation Ltd., https://www.openfoam.org/, 2024.

Referee Comment:

Page 8: CFD Model Development: In Fig 5, annotate each patch in the caption with its BC type. This helps readers match colors to physical conditions without looking at Fig 4.

Author Response:

Thank you for the suggestion. It has been implemented in the revised manuscript as requested.

Referee Comment:

Page 6-13: CFD Model Development: This section contains many typos. For example, “appropriated BCs” in Section 2.4 should be “appropriate BCs.” Also, ensure tense consistency—the writing should be in past tense throughout.

Author Response:

The consistency of terminology and verb usage throughout the paper have been thoroughly reviewed and standardized.

Referee Comment:

Page 13: Simulated Operating Conditions: Never seen a section as short as Section 3 before. That is why, a clear concluding paragraph with a concise "paper organization" in the introduction would have help you to keep all text tidy and simple to follow. In addition, you would recall that I mentioned, the cluster earlier. Why not move this entire section 3 to the paragraph and just provide more details.

Author Response:

Thank you for the suggestion. The previous Section 3 have been integrated into the preceding section. Additional details have also been introduced in the revised manuscript.

Referee Comment:

Page 6-13: Results and Discussion – Greases Distribution: The reviewer does not agree to this statement "This phenomenon is attributed to the influence of gravity". Other factors, such as rotation, are likely involved. Consider rewording to: "primarily due to gravity under rotation and tilt," unless more evidence is provided.

Author Response:

The sentence in question has been rephrased as suggested. Naturally, multiple effects are involved, and it is nearly impossible to isolate them completely. However, it is reasonable to state that gravity acts differently on the two bearing raceways, whereas the rotational speeds do not. Therefore, if differences emerge between the two raceways (or, more broadly, between the upstream and downstream regions), it can be inferred that gravity is the dominant influencing factor.

Referee Comment:

Page 13-18: Results and Discussion – Greases Distribution: Glad, now!!! Because the volume comparisons are valuable. Considered consolidating into a table, also instead of 0.0347001 m3, consider reducing the precision to 0.035 m3.

Author Response:

Thank you for the observation. A new table has been introduced, where these values have been reported and rounded to the third decimal place in the revised manuscript, which correspond to an approximation of 1 Liter.

Referee Comment:

Page 13-18: Results and Discussion – Greases Distribution: Figure 12 Panels: There are four subplots (a)–(d); ensure your text refers to each with consistent naming (e.g. “Fig. 12(a)” rather than “Figure 12a”).

Author Response:

Thank you for the observation. Nomenclature consistency has been implemented in the revised version of the paper.

Referee Comment:

Page 13-18: Results and Discussion – Greases Distribution: Your explanation that the stationary outer raceway starves is valid. consider adding a brief note on how cage geometry or gap width exacerbates this.

Author Response:

Thank you for your comment. Yes, several hypotheses can be made regarding the effect of cage geometry or gap reduction. However, these aspects have not been verified or investigated in the present study. The remarks included in the manuscript are based on findings reported in the literature.

Wen, Y. and Oshima, S.: Oil flow simulation based on CFD for reducing agitation torque of ball bearings, SAE International Journal of Passenger Cars-Mechanical Systems, 7, 1385-1391, https://doi.org/10.4271/2014-01-2850, 2014.

Zhu,W., Zhu, R., Tang, X., Lu, F., Bai, X.,Wu, X., and Li, F.: CFD-based analysis of oil and gas two-phase flow characteristics in double-row tapered roller bearings with different rib structures, Applied Sciences, 12, 1156, https://doi.org/10.3390/app12031156, 2022.

Referee Comment:

Page 13-18: Results and Discussion – Greases Distribution: Several captions lack full stops and unit annotations; ensure consistency

Author Response:

This point has been reiterated in the new figure captions.

Referee Comment:

Page 18-20: Results and Discussion – Fluxes: update some sign convention for clarity. You may define positive and negative axial directions (e.g. “positive axial velocity is toward the bearing bore”).

Author Response:

Thank you for the suggestion. It has been implemented as requested. Now the term ‘bearing bore’ is used.

Referee Comment:

Page 18-20: Results and Discussion – Fluxes: Discuss further on how the pumping effect might mitigate grease starvation at the top raceway under certain fill ratios.

Author Response:

This is a very important and distinctive aspect of tapered roller bearings. It can be stated that the pumping effect promotes continuous grease movement both along and away from the raceways, thereby limiting static accumulation in certain regions. This aspect, along with some observations based on our results at different initial grease fill levels, have been introduced in the revised version of the paper.

Referee Comment:

Page 18-20: Results and Discussion – Pressure Fields and Grease Settling Behaviour: In Section 4.3 you immediately mention Fig. 17, but the text doesn't specify which panel (a), (b), or (c) corresponds to which fill ratio. Make it explicit: "Fig. 17(a) shows 45 %, (b) 35 %, and (c) 21 %."

Author Response:

Thank you. The missing information has been added.

Referee Comment:

Page 18-20: Results and Discussion – Pressure Fields and Grease Settling Behaviour: But then again, you cite Maccioni et al. (2023a) but don't compare magnitudes. Add "their peak pressures were within 10 % of ours," to show consistency or highlight differences.

Author Response:

The initial text may not have been clear and has been rephrased. The authors are comparing the trend, not the absolute value. It is expected that the absolute value differs, given the significant differences in operating speeds and lubricant properties. The authors believe that comparing the peak value is not particularly relevant in this context.

Referee Comment:

Page 18-20: Results and Discussion – Pressure Fields and Grease Settling Behaviour: for the residual grease, what happens to the remaining 2 %? Discuss whether it remains trapped in pockets somewhere.

Author Response:

Unfortunately, it is not possible to make a precise statement on this point. Since an interface-capturing solver is used, the 2% volume is distributed over several cells and does not occupy at least 50% of any given cell. This means that the grease could be in contact with the surfaces, but the mesh resolution is not fine enough to confirm its exact position with certainty.

Referee Comment:

Page 18-20: Results and Discussion – Pressure Fields and Grease Settling Behaviour:

Again, the first paragraph in 4.4 covers two ideas (setup and results). Cannot be, consider splitting and move text to method and leave corresponding result text in results and discussion.

Author Response:

Thank you for the suggestion. It has been implemented as requested.

Referee Comment:

Page 25: Conclusion: observation the bearing reference code here as “41513219” is not correct, it should be “415132191”.

Author Response:

It is already correct. The ‘1’ is for the footnote. It is superscript.