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

Author Responses to Comments from Reviewer 1

Comment:

Line 12 Abstract: The authors present a CFD model for TRB main bearings of wind turbines. They simulate one full rotation with different fill rates of the bearing. They state their results emphasize the influence of gravity and bearing tilt. The reviewer wonders how to qualify this statement as something beyond trivial. In a relatively large bearing ring and at unrealistically low fill rates, it seems all too predictable the grease is flowing down. The key question for the remaining review of the paper is thus: Do the authors present any meaningful practical application of their model or at least an outlook to it?

Author Response:

We appreciate the reviewer's concern and the opportunity to clarify the significance of our findings. While it may seem intuitive that gravity causes grease to accumulate in the lower half of a large bearing at low fill rates, our CFD model provides a detailed, quantitative picture of this redistribution process—something that is not trivial to capture experimentally, especially in large-scale wind turbine bearings.

Some insights that can be obtained from this CFD model are:

1) Predict grease distribution across the bearing geometry during rotation, including zones that may experience lubricant starvation over time.
2) Assess the effectiveness of different initial grease fill rates under realistic gravitational and tilt conditions—information that can directly support maintenance planning and design of relubrication strategies.
3) Provide boundary conditions and input for wear, thermal, or life prediction models, particularly for large and costly systems like direct-drive wind turbines, where over- or under-lubrication can have serious operational impacts.
4) Evaluating seal pressure under various conditions to assess the risk of grease leakage, which is a key concern in operational reliability.

In this study, the grease distribution has been studied in detail in terms of volume in each raceway and upper and lower portion. The pressure on the seals is another important aspect to study to have idea about the grease leakage that can occur through seals if the pressure is beyond the limit. The grease velocities and pumping effect play important role in the lubrication phenomenon that can be studied through this CFD model for large-scale bearings.

This study was conducted in collaboration with a wind turbine manufacturer that employs double-row tapered roller bearings in their direct-drive wind turbines. The primary objective was to investigate the behaviour of grease within the bearing under operational conditions. Specifically, the company was interested in understanding the effect of bearing tilt on the grease distribution between the two rows, as well as the pressure exerted on the seals—an important factor in assessing the potential for grease leakage. The grease fill rates used in the simulations were selected in consultation with the company, based on their input that in real operating conditions, the fill is typically below 50%. Indeed, the company typically operates the bearings with a grease fill ranging from 40% to 50% of the volume. However, there is currently no established method to determine whether this amount is truly optimal. On one hand, a higher grease quantity could extend the component's service life, but it would also lead to increased load-independent power losses and elevated pressure on the seals. On the other hand, reducing the grease quantity would undoubtedly yield benefits in terms of lower power losses and reduced seal pressure, but it may also compromise the longevity of the components due to insufficient lubrication and premature wear.

This is precisely where our CFD-based approach becomes valuable: it enables us to estimate the capability of a reduced grease quantity—potentially considered unrealistic today, as noted by the reviewer—to effectively reach and lubricate the critical contact zones within a reasonable time frame. After all, the purpose of research is to explore such future-oriented scenarios, which may one day become standard practice.

This explanation has been included in the revised manuscript.

Comment:

Line 20 Introduction: While all of the first paragraph is correct, I think it is not stricly necessary to state these points in a journal called 'Wind Energy Science'. I think it is safe to assume the community around this journal is well aware of the role of wind energy and the need for reliable turbine operations.

Author Response:

Thanks for this suggestion. The introduction in revised manuscript has been streamlined, focusing only on the essential elements needed to contextualize and describe the work.

Comment:

Line 22 Introduction: 'play a significant role in enabling efficient rotation' - this is a awful lot of words to express that they 'allow rotation', isn't it?

Author Response:

The sentence has been revised.

Comment:

Line 25 Introduction: In comparison to other rolling bearing types, TRBs have a combination of features which makes them suitable for this applicaiton:

1. The one you mentioned already

2. The absence of slip in the contact under kinematic conditions

3. Due to line contact a high strength in radial direction.

If you only mention the first aspect, this falls a bit short because other bearings types such as angular contact ball bearings or four-point contact ball bearings or three-row roller bearings share the ability to carry radial and axial loads.

Author Response:

Thanks for giving this information. All these applications have been included in the revised version.

Comment:

Line 29 Introduction: Here is a space too much, also the statement of DRTRB being the most widely used main bearings is very bold. If you go by numbers, SRBs might still be

Author Response:

Thank you for this observation. Double-Row Tapered Roller Bearings (DRTRBs) and Spherical Roller Bearings (SRBs) are supported in the literature as suitable configurations for use as main bearings in wind turbines. The reference is provided here.

Hart, E., Clarke, B., Nicholas, G., Kazemi Amiri, A., Stirling, J., Carroll, J., Dwyer-Joyce, R., McDonald, A., and Long, H.: A review of wind turbine main bearings: design, operation, modelling, damage mechanisms and fault detection, Wind Energy Science, 5, 105–124, https://doi.org/10.5194/wes-5-105-2020, 2020.

The statement has been revised in the manuscript.

Comment:

Line 33 Introduction: Please check if this subscript is meant to be in italic letters. Apply this check to all signs in the paper.

Author Response:

Thanks for pointing this out. It is used in italic letters in the literature. All the signs have been checked and made consistent in the revised manuscript.

Comment:

Line 37 Introduction: If this is in the past, should mankind then stop developing now?

Author Response:

The Introduction section has been revised.

Comment:

Line 37 Introduction: bearings

Author Response:

The Introduction section has been revised.

Comment:

Line 39 Introduction: focusing on

Author Response:

The Introduction section has been revised.

Comment:

Line 39 Introduction: "CFD tool" - is there only one? Or do you refer to CFD methods?

Author Response:

Thanks for pointing this out. The Introduction section has been revised.

Comment:

Line 40 Introduction: coefficient

Author Response:

The Introduction section has been revised.

Comment:

Line 40 Introduction: roller - just one? Or does it have more than one?

Author Response:

It has been rectified in the revised manuscript.

Comment:

Line 40 Introduction: Please rewrite this sentence in active voice and drop the gerund: Marchese ... and Gao .. used single-phase CFD to...

Author Response:

Thanks for this suggestion. The sentence has been corrected.

Comment:

Line 44 Introduction: There is a verb missing here

Author Response:

The Introduction section has been revised.

Comment:

Line 45 Introduction: Singular / Plural. At this point, I will stop correcting language errors. I recommend using professional proof or translation services.

Author Response:

Thanks for pointing out these grammatical mistakes. The revised manuscript has been proofread, and grammatical mistakes have been corrected.

Comment:

Line 49 Introduction: How do you apply a study to a TRB? Do you stuff the paper into the bearing?

Author Response:

Thanks for pointing out this unclear phrasing. It has been revised and rectified.

Comment:

Line 49 Introduction: This entire introductory section mostly states that some authors have used different CFD tools but provides very little information on the results of the studies and thus lacks important information. Almost every sentence contains laguage errors (signular, plural, verbs missing, pronouns and prepositions wrong) and style issues (extreme use of passive voice and gerunds). I am sorry to say this, but there is a lot of potential to improve thisl.

Author Response:

Thanks for pointing out this inconsistency. The results from respective literature have been included in the revised manuscript.

Comment:

Line 56 Introduction: Same as before paragraph, this one merely lists a number of publication and rughly outlines their subject. It does not state the result of these nor gives any additional information. I think this should be extended significantly. Perhaps it makes sense to have fewer, but more related citations and then give details for each.

Author Response:

In the revised version of manuscript, the introduction has been enriched with the results obtained from the literature.

Comment:

Line 91 CFD Model Development: While I can fantasize about this being because else there is no lubricant flow in and out of the contact, I do not know if this is right and I think it merits some explanation.

Author Response:

Thanks for seeking this clarification. This method is already used in the literature. It helps in the refining of mesh near the walls to avoid any triangular cells and to obtain better numerical accuracy.

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.

Comment:

Figure 1(b): As a bearing engineer, the areas marked as raceways in this figure make me shed a tear or two. Raceways are the things the rolling bodies are in contact with. The area marked in red contains the outer raceways (there are two), but also other ufnctional elements of the bearing. Please be more precise.

Author Response:

Thanks for this observation. You are correct that raceways, in the strict sense, refer only to the contact surfaces where rolling elements interact with the bearing rings. In our figure, the term “raceway” was used more broadly to denote the full regions associated with either the inner or outer ring components, including both the actual raceway surfaces and adjacent functional zones. The classification was based on the relative motion of these parts: regions labelled as “inner raceway” move with the inner ring, while those marked as “outer raceway” remain stationary with the outer ring.

However, in the revised manuscript, the figure has been changed according to the suggestion. Now the raceways show only the area of contact.

Comment:

Table 1: Please state the cone angle, contact angle, and roller length.

Author Response:

The table has been updated.

Comment:

Line 96 Meshing of Double-Row TRB: 'A systematic approach to initiate the meshing process' - this sounds very important, perhaps even a bit too important for the thing it describes. I think most rolling bearing raceway systems are rotationally symmetric (else it is a tad difficult to rotate them) and this symmetry is used in any meshing of bearing unless you love someone to do manual work.

Author Response:

We thank the reviewer for this valuable observation. Indeed, the rotational symmetry of rolling bearing raceways makes it natural to exploit this feature during meshing. Our intention with the phrase "a systematic approach to initiate the meshing process" was to highlight the specific challenges and steps involved in using OpenFOAM's blockMesh utility, where all vertex coordinates must be explicitly defined, and mesh blocks manually constructed.

The first major issue stemmed from the fact that the bearing consisted of 65 sectors—an odd number. As a result, a simple mirroring approach was not viable, since mirroring would produce an even number of sectors (e.g., 64), leaving the 65th sector unaccounted for. Creating the final sector manually and attempting to stitch it to the existing mesh carried a high risk of misalignment at the interface, potentially compromising mesh quality and numerical accuracy.

The second challenge was related to the scale and complexity of the bearing. Due to the large number of cells involved—on the order of millions—it was impractical to manually define all vertices, blocks, and arc segments directly in OpenFOAM using the blockMeshDict file. OpenFOAM does not automatically generate vertices; each one must be explicitly declared.

To address both of these issues, a custom MATLAB script was developed to parametrize the geometry and automate the generation of vertices, blocks, and arcs. This approach ensured consistency, accuracy, and scalability in the mesh generation process.

This subsection has been revised which includes all the relevant information and details regarding mesh generation.

Comment:

Line 97 Meshing of Double-Row TRB: was it necessary to rotate it systematically? Or could you simply rotate it? What is the difference and why this adverb here?

Author Response:

Thanks for this observation. The use of the word "systematically" was intended to emphasize that the rotation of the mesh was not a straightforward duplication or geometric transformation.

In our case, the bearing geometry was divided into 65 sectors, and each sector's mesh had to be generated with precise control over the vertices and block connectivity.

Since we used OpenFOAM's blockMesh utility, which requires manual specification of all vertices and blocks, it was necessary to programmatically rotate the initial sector and exclude common points at the sector boundaries to avoid duplication errors—something that blockMesh does not handle automatically. This process required a systematic and parametric approach to generate the mesh efficiently and accurately.

This explanation has been included in the revised manuscript.

Comment:

Line 136 Meshing of Full Bearing: I must admit I never worked with OpenFoam, but more with structural FE preprocessores - rotating a mesh around an axis and deleting overlaying nodes is a standard functionality for most of them, and it seems really odd that you had to do something with Matlab to get this done. If this is truly the case and it was absolutely novel to do this, kindly mention in your leading explanation that Openfoam does not do that automatically. Else reconsider omitting this entire subsections 2.2.1 and 2.2.2

Author Response:

Thanks for this insightful observation. Indeed, many structural FE preprocessors include built-in tools for rotating geometries and automatically handling duplicate nodes. However, in OpenFOAM's blockMesh utility, this functionality is not available by default. All vertices, blocks, and arcs must be explicitly defined, and there is no built-in mechanism to automatically remove or merge overlapping points after rotation.

In our case, the mesh consisted of 65 sectors forming the full geometry of a double-row tapered roller bearing. Manually creating this mesh by defining every point and block in the blockMeshDict would have been extremely time-consuming and error-prone. Therefore, we developed a MATLAB script to automate the parametric generation of the mesh, including:

- Rotating the base sector,
- Avoiding duplicate points at sector boundaries,
- Defining all necessary hexahedral blocks and arcs.

This approach allowed us to create a high-quality, structured hexahedral mesh suitable for CFD analysis of large-scale geometries.

We have updated the manuscript to clarify that this workaround was necessary due to limitations in OpenFOAM's native tools.

Comment:

Line 150 Key Parameters of Mesh Quality: Please elaborate a bit on the why. Which aspect ratio would be inacceptable?

Author Response:

Thanks for pointing this out. The aspect ratio is an important parameter in assessing mesh quality, particularly in narrow regions such as the grease film between rollers and raceways. In our case, the maximum aspect ratio was 13, which we consider acceptable given the high-aspect geometries involved in the bearing clearance regions.

Aspect ratios significantly higher than this—typically above 20—can lead to numerical inaccuracies due to poor gradient resolution and increased interpolation errors. By maintaining an aspect ratio of 13 or lower, we ensure adequate resolution in the normal direction (especially across the film gap) without excessively increasing the overall cell count. This balance allows us to resolve the shear and pressure gradients accurately, particularly in zones critical for grease flow and pressure buildup.

This explanation has been added in the revised version of manuscript.

Comment:

Line 155: Again, I did not use openFoam so far, but this reads like ti is from the manual. If it is, then you should make a proper reference.

Author Response:

Yes, the reference has been added in the revised manuscript.

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

Comment:

Table 2: It hurts my eyes to see a centered numerical column in a table. Unless this is some offbeat art project, don't. Align by the decimal separator and keep that to the right.

Author Response:

The table has been updated according to suggestion.

Comment:

Line 174: Why is this explained here?

Author Response:

This subsection has been revised according to reviewer's remarks.

Comment:

Line 181: contact angle.

Author Response:

Thanks for this observation. The statement has been revised.

Comment:

Line 183: Jesus, no. It is not. You describe the contact angle.

Author Response:

Yes, you are right. It has been corrected accordingly.

Comment:

Line 185: This explanation is not true because you make it sound like it is something proprietary for double row TRBs, whereas it is precisley the same for single row TRBs. Also, it is not only the contact angle apex point that ensure pure kinematic rolling, the cone angle (not alpha!) is necessary as well.

Author Response:

You are right. We have rephrased the sentence in the revised manuscript to avoid this confusion.

Comment:

Section 2.3.4: This section seems to completely omit one fundamental property of grease: They are made up of two phases (thickener and base oil) which interact in various, sometimes hard-to-predict way. One famous example for this interaction if the 'bleeding' of oil from the grease.

Author Response:

Thanks for pointing this out. Indeed, grease is a multiphase material typically composed of a base oil and a thickener, and interactions between these phases—such as oil bleeding—can significantly influence lubrication performance. However, in the present study, grease is modelled as a homogeneous non-Newtonian fluid using the Herschel–Bulkley formulation, which captures its shear-thinning and yield stress behaviour. This simplification allows us to focus on the global flow and distribution characteristics of grease within the bearing.

The reference has been provided accordingly.

Perez, J. M.: Lubrication Fundamentals, CRC Press, Boca Raton, FL, 2004.

This section has been revised to include these details.

Comment:

Section 2.3.4: From personal experience: Grease (and oil) has a tendency to stick to surfaces. Am I right in assuming that this peroperty is not taken into account int he simulations?

Author Response:

Yes, in the current CFD model, this adhesive property is not explicitly accounted for. The interaction between grease and solid surfaces is simplified by applying standard no-slip boundary conditions.

Perez, J. M.: Lubrication Fundamentals, CRC Press, Boca Raton, FL, 2004.

Comment:

Table 5: I fail to understand the motivation behind these variations. Grease-lubricated bearings in wind turbines are commonly filled to a very large extend, if not during manufacturing than in later oepration because of the grease refills (automatic or manual). What are you trying to show or understand here and how does it relate to real wind turbine operation?

Author Response:

Thanks for seeking this clarification. 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.

These fill ratios were chosen in consultation with wind turbine company.

These details have been included in the revised manuscript.

Comment:

Line 233: What kind of critical operating condition is this? Please elaborate.

Author Response:

Thanks for pointing this put. This is considered a critical operating condition because the lubricant level is set just below the outlet ports. At this level, the lubricant is on the verge of being unable to reach the outlet, which means any further drop in lubricant quantity would prevent it from flowing out of the bearing. This represents the minimum lubricant level that can still maintain functional operation, making it critical for ensuring proper lubrication and system reliability.

This explanation has been provided in the revised manuscript.

Comment:

Figure 7: I do not see this depiction as necessary, I personally am able to have a rough idea of volume percentage in my head without it.

Author Response:

We understand this perspective and agree that experienced readers may estimate volume percentages intuitively. However, the depiction is included purely for visualization purposes, to provide a clear comparison of different grease levels within the bearing. It helps illustrate how the distribution changes under various filling conditions, which can be useful for readers less familiar with such systems or for communicating the setup to a broader audience.

Comment:

Line 237: Why do you simulate just one rotation? Does the wind turbine stop after one rotation? Or is this for computational reasons?

Author Response:

Thanks for pointing out this. It is due to computational reasons. It is for the first time that at this large-scale mesh is developed. It requires very high computational power. The physical time required for running one simulation was 45 days. Therefore, it was decided to study only one rotation of cage.

In addition, we observed that, in most cases, less than a single cage revolution is sufficient for the grease—regardless of the initial fill level—to reach the upper part of the bearing. As such, simulating one full cage revolution has consistently proven to be adequate for obtaining the information relevant to our study.

Comment:

Line 238: I think the term grease starvation is not correctly used throughout the paper. Bit maybe I am wrong, so kindly supply a reference for your use of it so I can look it up.

Author Response:

The term grease starvation is used for areas where there is no sufficient amount of grease present. Several studies have used this term.

Cann, P. M., Spikes, H. A., & Hutchinson, J. (1996) "The development of a spacer layer imaging method (SLIM) for mapping Elastohydrodynamic contacts." Tribology Transactions, 39(4), 915–921.

Arya, U., Sadeghi, F., Aamer, S., Meinel, A., and Grillenberger, H.: In Situ Visualization and Analysis of Oil Starvation in Ball Bearing Cages, Tribology Transactions, 66, 965-978, https://doi.org/10.1080/10402004.2023.2253867, 2023.

Comment:

Figure 8: I think it would make very much sense to match these visualization with the load distribution in this bearing. Is the low grease volume at the top really critical?

Author Response:

Unfortunately, detailed load distribution data was not shared by the industry partner due to proprietary constraints. However, based on discussions with their engineering team, it was communicated that the upper region of the bearing is considered critical in their application. This concern is likely linked to operational tilt and transient loading conditions, which may cause periodic load transfer to the upper rows, particularly during wind gusts or dynamic yaw moments.

Also, the reference is provided which provides force-moments balance.

Hart, E., Clarke, B., Nicholas, G., Kazemi Amiri, A., Stirling, J., Carroll, J., Dwyer-Joyce, R., McDonald, A., and Long, H.: A review of wind turbine main bearings: design, operation, modelling, damage mechanisms and fault detection, Wind Energy Science, 5, 105-124, https://doi.org/10.5194/wes-5-105-2020, 2020.

Comment:

Section References:

Author Response:

The references have been thoroughly revised and presented in standard format in the revised manuscript.