Wind turbine main-bearing lubrication - Part 2: Simulation based results for a double-row spherical roller main-bearing in a 1.5 MW wind turbine

Response to reviewer 2

Dear reviewer,

First, we would like to thank you for your considerable efforts in assessing our manuscript and suggesting improvements. We will make ensure the updated manuscript includes the suggestions you have made here.

A detailed response is now provided. We include your comments below in **blue**, followed by our responses in **black**.

The submitted paper discuss the lubricating conditions of main-bearings of wind turbines using a double-row spherical roller bearing in a 1.5 MW wind turbine as case study. In the reviewer's opinion the submitted paper is well written and structured. However, the scientific significance of the applied approach is limited. Understandably the authors apply known methods and a significant number of assumptions, however, this leads to the question of how the proposed approach differs from the typical industrial approach.

In response to this point, and some others below, it is important to discuss the aims and position of this paper in the context of the literature for main-bearings in wind turbines. The main-bearing is a component which has been identified as a problem for the wind industry, but one for which the literature has been relatively sparse until recently. A growing number of studies have now considered various aspects of the operation and reliability of this components, but, before now there have been no papers whatsoever which consider lubrication and EHL conditions for this component. Since the main-bearing is a tribological and lubricated component this aspect of its operation must be included if the premature failures seen in the field are to be properly understood and ultimately prevented. The difficulty when it comes to understanding this component is the fundamentally multi-disciplinary nature of the problem, since it is a bearing affixed to a flexible structure whose input loads are complex and determined by interactions between the wind turbine rotor and turbulent wind fields. Bringing these various aspects of the problem together necessitates simpler analyses to begin with, in order for important aspects and interactions to be identified – allowing areas for further analysis (using more sophisticated models) to be identified and prioritised. This paper represents that first effort for main-bearings in wind turbines. As such, we don't necessarily claim that we are doing things very much differently from the current industrial approach, but, the methods we use are applied transparently and with careful consideration of their validity and limitations etc. Furthermore, the industrial work on main-bearings you refer to isn't available in the public domain and so can't be built on as ours can. Finally, as with the review portion of the paper, a principal aim here is also the promotion of interdisciplinary understanding for engineers in related disciplines to be able to perform similar analyses and understand how our results impacts them. The current paper also achieves this goal and is the first to do this (for the main-bearing), this is another aspect of the paper's novelty, in addition to the new knowledge being presented here for this component. Overall we believe that this paper presents a solid foundational set of results, using existing methods applied with careful consideration, which lays the groundwork for further work and more sophisticated analyses.

The authors focus on reaching a wider readership by using simplified descriptions and methods. While this approach seems reasonable for part 1, it leads to the major short-coming of part 2: apparent missing novelty. In the reviewer's opinion the submitted paper could be shortened significantly and complemented with further aspects such as: consideration of sliding (due to the formation of a load zone, due to low loads and along the contact line - Heathcote slip), in-depth analysis of temperature distribution, lubrication type, geometry (such as modern tapered main-bearings), starvation….

As described above we believe these is important novelty in this paper already. In future work we are going to be working on some of the things you mention here, but they fall outside the aims and context of this work. For example, wind turbines never see steady operating conditions, as such analysis of slip requires a fully dynamic main-bearing model. Such a model will require significant development beyond our current capabilities and so falls out of scope for this work at present. Similarly, an in-depth analysis of the temperature distribution would require thermal modelling of the main-bearing is not yet available in our model. With respect to temperature we know that the temperature range we study is close to the values seen in practise and, importantly, the results indicate that these temperatures may be seen as a change point between lubrication regimes. This result is valuable and important in of itself and indicates where future analysis should be focussed. As stated above, we believe the results presented provide an important baseline on which to build. We agree that the analyses you suggest should be undertaken, but we believe they fall into the category of 'recommended future work'.

In the reviewer's opinion the submitted paper is a case study rather than a research paper.

Since this paper focusses on an individual wind turbine and a specific main-bearing it is perhaps fair enough to consider it a 'case study'. I don't agree that this means it is not also a 'research article'. As outlined above, this is the only article in the literature which has presented results of this nature for a wind turbine main-bearing, meaning it provides important research novelty despite focussing on one specific turbine and bearing.

Please consider following points:

Abstract

• The temperature should be introduced as an influencing factor.

We will add this as suggested.

Introduction and Background

• The authors state that

 o "higher than expected failure rates" and "premature failures in main-bearings" occur. Please quantify and give the necessary references.

We will add numbers and references to this when revising the paper

 o "it cannot currently be known a priori whether main-bearing failure rates are likely to be improved or worse". In the reviewer's opinion the authors could discuss whether the contact conditions would most likely positively or negatively impact the lubricating conditions (speed, load, time between contacts and temperature could be compared).

We will consider if more context/discussion can be given here

 o "fatigue life assessment……explicitly assumes EHL". Modern lifetime calculations do not assume EHL. For example, the aiso or the askf consider the lubricating conditions through the viscosity ratio Kappa.

Thank you for pointing out this error, we will correct when revising the paper

 o "the described load structures were found to drive large, rapid variations..". Please quantify.

We will add concrete numbers here

 • Based on the investigations in Guo et al. (2021) the authors state that axial motions are slow and highly unlikely to impact the lubricating film. However, they state that "the lubrication was not modelled directly". In this case, how was the aforementioned conclusion drawn?

In that work, the maximum axial speed of the rollers was expressed as a percentage of entrainment velocity, then this was compared with results in the literature regarding when the axial motion will disrupt the EHL film. Their % was lower than that given as the cutoff in the literature, hence they concluded that axial motions were unlikely to be impacting the lubricant film. We will make this clearer when revising the paper.

• Sentences 29 through 38 are a good example of strongly simplified explanations which could be strongly shortened

We will see about shortening this.

• Please give the coordinates of the two radial components of the load vector

Will do.

Methodology

• Please use references where is appropriate (e.g. IEC design standards)

We will add these in

• Could the authors please state if “10 min.” refer to simulation or operation time?

Operational time, we will make this clear in the manuscript

• The authors explain that the applied force was considered (instead of the reaction force). Furthermore, they explain that it is necessary to ensure the correct one is calculated with the respect to the reference frame. How do the results will deviate if the reaction force is used instead? They have equal magnitude

This is important for tracking the loads on individual rollers as they move around the main-bearing. The Hertzian contact model takes an input of the applied load vector, with the vector direction determining the location of applied load etc. The rollers are simultaneously orbiting the bearing centre and so their positions relative to applied loading matters. If the reaction load is used the load will be of the correct magnitude, but acting in the wrong direction and so maximally loading the wrong rollers.

• Please comment why the upwind row is “only occasionally loaded during normal operations”. One would expect that the radial load is carried by both rows

A wind turbine sees very large thrust loads, this causes axial deflections which tend to unload the upwind row throughout much of the operating time of the turbine. The second row is there mostly for when the turbine if not operating. This is shown in https://doi.org/10.1002/we.2549 and also provides motivation for the design changes proposed in https://doi.org/10.1007/s10010-021-00462-1

• In the reviewer’s opinion the authors should expand their consideration of roller sliding. It is well known that sliding have a great impact on the contact temperature and the film formation

As mentioned above, a wind turbine never sees steady-state operating conditions and so standard sliding models cannot be used to evaluate this. A full dynamic model would be needed instead. This is something we intend to develop but not a capability we have at this time. Furthermore, it is our understanding that sliding will indeed affect the bearing temperature through friction, but that its effect on film thickness is relatively small because it is the viscosity (and hence temperature) of the lubricant at the contact inlet that most directly determines film height. So, the main effect of sliding would be to elevate the overall temperature of the main-bearing. But, this is something we already account for indirectly because the temperature range we use is based on measured temperatures of operating main-bearing casings (we’ll revisit this topic in a later comment).

• The authors comment that “other details are proprietary”. In the reviewer’s opinion profile and roughness measurements can be carried out and consider in half-space calculations

We will consider if more information can be given.

• Table 1

 o The combine surface-roughness seems high. Please give the individual values and the method used for determining the roughness

We will need to check to see if individual values can be given. These are combined by taking the square-root of the sum of squares of the values.

o Please comment on the profile in width-direction

We will see if this is information we have available to us.

o "Inlet temperature" is commonly used for "lubrication nozzles". Please consider writing "contact inlet"

We will do this as suggested

• In the reviewer's opinion the selected temperatures could be too low. If the outer bearing casing is at 20-40 °C degrees the contact temperature (most likely) won't be in the range between 30 - 40°C. How did the authors make this assumption?

These are low speed bearings and so, based on information we could find on casing versus internal temperatures, we don't expect the internal temp to be much higher than that of the casing. In addition, and as discussed in the paper, the values are chosen because they are certainly within the normal operating range for a wind turbine main-bearing (based on available data) but also because they represent a transition point between lubrication regimes. Higher temperatures are possible, but this would only strengthen the conclusion of the paper that mixed lubrication is expected.

• Sentences 177 through 185 are a further example of strongly simplified explanations which could be strongly shortened. In which cases would the authors consider a spherical-roller bearing as a point contact (aside from insignificant loads)?

Our definition of point contact, as given in "Part 1", includes both circular and elliptical contacts. Therefore, yes we consider and SRB roller to be a point contact in the context of Hertzian theory. However, as shown in the paper, we argue that it should be treated as a line contact for the purposes of EHL film analysis.

• One could argue that the consideration of starvation is not scientifically accurate. In the reviewer's opinion the authors should either select a concrete approach or take the sub-chapter out. If the authors decide to expand this chapter please consider modern literature regarding starvation and the influence of base oil and thickener on the film formation.

We agree that this analysis of starvation is limited. But on reviewing the most recent available literature on starvation (as suggested by yourself in "Part 1" – where the starvation section is now much expanded), it remains the case that current analytical formulas are not yet at the stage where they may be practically applied to a full bearing. However, we believe that the analysis as presented still provides useful information by considering the impacts of film reductions of the general order of magnitude seen during starvation. This helps show that starvation is a key consideration for this main-bearing since it could be the different between full EHL and mixed lubrication. But on reflection we think that this part of the analysis could be better presented in the context we have described it here. Therefore, we will revise the description, motivations and interpretations of this part of the analysis carefully.

Results

• Sentences 231 through 240 are a further example of strongly simplified explanations which could be strongly shortened.

We will consider shortening this.

• Please consider using the shaft speed instead of the wind speed for Figure 10.

I assume you are referring to Fig 2. Windspeed is used as this is the variable that dictates the operating point of a wind turbine. The rotational speed of the wind turbine only changes for part of it's operating range and so would result in a less clear figure. Furthermore, the 'speed' from a lubrication point of view is represented by the dimensionless viscosity/speed parameter L. For these reasons we believe wind speed is the better candidate for the colorscale.

• In the discussion of Figure 10 the authors state that around the bearing circumference an unloaded region is generally included. While this is true for radial loads the authors stated before, that the down-wind bearing was used as case study. This bearing is

supposed to be axially loaded, which could result in a load zone over 360°.
Yes this is indeed correct, and 360 degree loading can happen, but it is more common that not that there will be an unloaded region on the bearing. This comment is there to explain why a full range of M (dimensionless load) values is seen across all wind speeds – and the abundance of M values of the left shows that unloaded rollers are common.

- The authors explain that "outlying points at very low loads correspond to high values of film thickness". Please mark this points int Figure 10

I am not sure if this needs to be pointed out on the figure itself, since the load is captured by M directly. But, we will make sure when revising the paper to specify those values more clearly as related to M. We will also consider whether to add anything to the figure for clarity.

- Please revise sentence 254-255. It gives the impression that the load is the determining influencing factor

Will do.

- It is commonly known that the pressure increases in the area of the PETRUSEVICH-peak. How do the authors assume that the maximum EHL pressure values are equivalent to those seen in dry contacts?

We use the Hertzian contact pressure as an estimate of maximum pressure in the conjunction, which is the case for heavily loaded rollers (we discuss this in "Part 1" of the paper). We will make this clearer in the manuscript.

- Did the authors consider the axial load in the pressure calculations?

Yes, pressure values were calculated after the Hertzian contact model was used to evaluate all rollers loads under both radial and axial loads applied to the bearing.

- Please comment whether the minimal loading of the bearing is guaranteed and how this affect its sliding behaviour

For an SRB in a wind turbine, minimal loading is not guaranteed as there is no preloading. As has been shown in previous work https://doi.org/10.1002/we.2549 unloading of the main-bearing can occur during operation. This would likely introduce sliding into the system but we are not yet able to quantify this effect.

- Please give the used formula for lambda

We will add this in.

- Please comment if the selected variations step in table 2 are plausible. Furthermore, the magnitude of pressure influence is dependent on the load magnitude (as shown in Fig 3.), therefore, the simplified statement that by reducing the load by 50 % the lambda value increases by 6 % is misleading.

Yes these are plausible changes in variable values based on the data available to us. We will look to make sure that the reasons for this are given in the revised manuscript. With respect to the pressure/load comment I believe you are referring to the fact that the change in film thickness with change in load is different at different loads. This is certainly true, although the same is also true for the other varied parameters, e.g. temperature, when they are changed. But, please note that the values given in the table are average values of changes in Lambda from sensitivity testing across the whole dataset of operating points. Therefore, this includes the fact that changes are different at around different operating points.

- Why did the authors consider the bearing as a point contact for chapter 4.3?

Again we should clarify that our definition of point contact includes both elliptical and circular contacts. Here we are treating it as a long elliptical contact. For lubrication it was treated as a line contact for reasons that were outlined. But in 4.3 we need to understand changes in its dimensions as an elliptical contact (changes in both a and b) since this is what it is. The reasons that we needed to use equivalent line contact equations before do not apply here, and so it was deemed appropriate and necessary to perform an elliptical contact analysis.

- Why was a threshold of 25 % selected? Please add references

We will add a reference for this.

Discussion and conclusions

• The authors should discuss the influence of running-in

We will look to include this in the revised paper.

• No further comments. Please consider the points above