

Dear Jonathan Keller,

Thank you for the comprehensive and helpful review of the proposed paper. From my point of view the quality of the paper has been improved by incorporating the suggested changes. Please find my answers, comments, and changes below:

**General Comments:**

I tried to understand your general comment to the proposed paper and felt that some parts of it can indeed imply a misleading understanding of what the work is about. In fact, the paper is not intending to present control strategies which are lowering the risk of wear or to do a comprehensive comparison between different controllers and different site-conditions. Instead, the paper can be better understood as a case study aiming at assessing and testing the wear risk of an individual pitch-controlled turbine under the influence of site-specific wind conditions. Therefore, some methods are presented which can be used to evaluate the wear risk by testing and which revealed that wear can occur in a rather short time frame of only several hours of operation. To avoid misleading expectations about the content we incorporated several changes as suggested in the specific comments section. In addition, the abstract has been changed from line 12 onwards to a less universal or comparative assessment of the wind and operating conditions:

*This work analyses exemplary wind and operating conditions of one specific site regarding their influence on wear in blade bearings. It is based on measured wind conditions and the modelled behavior of the individual pitch-controlled IWT-7.5-164 reference wind turbine with respect to its pitch activity.*

I will try to answer some of your more general comments in the following.

- After giving some thought about trying to sum up the article in a single sentence, I personally would conclude that the work shows that “Pitch bearing wear can quickly result from individual pitch control”. Can that be as broadly implied as written? Or does it entirely depend on the nature of the site, turbine, and such?

Your takeaway is correct. However, as discussed in section 6 it should be noted, that while it is possible to derive this more generalized statement, different site-specific wind conditions and controller characteristics can lead to a different result. Hence, the proposed methodologies can be used to assess the individual wear risk for example by running scaled tests.

- Can we quantify in anyway what we thought the risk of the conditions might have been, compared to what they were demonstrated to be?

At this stage, there is no documented and straight forward way of assessing and quantifying the wear risk during the design process of the pitch controller. In addition, and as mentioned in the discussion section I am not aware of an on-demand lubrication run strategy at this point. Future work will address this and will provide suggestions for this.

- Then again, maybe a more important point is that the actual site-specific characteristics might give different results than the standard IEC classes – maybe the latter would yield little to no wear?

Despite the different characteristics of this exemplary site with respect to turbulence intensity and vertical shear in comparison with the IEC standards, especially the lack of a suggestion on medium-term behavior of the wind makes it difficult to assess the wear risk with respect to the IEC classes. The order of occurrence of operating conditions over the periods of hours and days is the challenge of determining the wear risk.

## Specific Comments:

- Title: I have to wonder, is the aspect of “site-specific” worthy of being in the title? It is certainly true that this examination was accomplished using the particular wind characteristics of an actual site and for a reference (or representative of the state-of-the-art) large, modern wind turbine. But, I believe those to be secondary. Would the authors agree? It was also not shown/quantified (or at least I didn’t pick up on it) that the site-specific conditions were any more problematic in terms of wear than standard IEC wind classes and NTM. I think a simpler title like “The effect of individual pitch control on blade bearing wear” is more accurate and better in line with the Test Results, Discussion and Conclusions.

The site-specific wind conditions are characterized by a specific composition of wind speed, turbulence intensity, vertical shear. The important aspect of those wind conditions with respect to wear damage of blade bearings is the order of occurrence and overall duration of wear critical periods. This aspect is usually not covered by design processes of pitch controllers or operating strategies of blade bearings, but as a conclusion, should be looked at. Hence, I believe that the term “site-specific” is of importance for this work. However, to lower the risk of misleading impressions on the context of the paper the abstract has been changed as mentioned in the general comment section.

- Abstract: I think it is common that the Abstract should be a single paragraph. I also think what is now the second paragraph can be improved to be more specific as in “This work demonstrates that a site-specific wind and pitch controller conditions can quickly result in pitch bearing wear.” That is, the article doesn't generally analyzes (plural) “wind and operating conditions”, just one particular combination. OK, across wind speeds yes, but really seems to be specific to this particular site. I also recommend adding the adjective “mild” to wear in the Abstract to be in line with the last sentence in Section 6.

Thanks for the suggestions and you are right with some misleading formulations. In addition to the changes mentioned in the general comment section I implemented the term “mild wear”.

- 1 Introduction: There are some minor grammatical changes needed here. In line 29, I recommend “...for evaluating the wear risk to pitch bearings...” This paragraph is also only 2 sentences long. I believe it can be combined with the next paragraph beginning on line 31.

The short paragraph beginning in line 29 is now combined with the former one.

- 1 Introduction: The sentence describing  $\theta_{crit}$  in lines 32-33 can be improved, specifically “gets in touch”. I believe per DG03 and per Rumbarger and Jones that  $\theta_{crit}$  is “the relative angle of rotation of the raceways for which the portion of the raceway stressed by one rolling element touches—but does not overlap—the raceway that is stressed by adjacent rolling elements.”

The description of  $\theta_{crit}$  has been updated to match the formula expression of the DG03 as follows:

*$\theta_{crit}$  is the oscillation angle of the inner raceway relative to the outer raceway for which the center of the contact of one rolling element moves to the initial center of contact of the adjacent rolling element.*

- 1 Introduction: The sentence on lines 36-37 also says “Tests on small scale bearings performed by showed...”, which reads as though a name and/or reference is missing, or “performed by” can be deleted. I suggest the former though.

Thanks for noticing. “performed by” has been deleted.

- 1 Introduction: I will admit I got a bit confused reading lines 40 – 47 and “the work related to this paper focuses”, lines 53-54 and “aim of this test program is to”, and lines 57-58 and “The study in this paper is not”. I kept thinking that they were describing this manuscript, when I think they are describing nearby citations. I recommend these be past tense and/or “this” changed to be more specific. The statement about this manuscript does not come until lines 76-79. Generally speaking, I found lines 45-75 a bit hard to follow. It might also help to begin a new paragraph with “Stammler (2020)...” on line 47 and maybe trim some of this material in lines 47-75. At a minimum, I would suggest defining the acronyms for HBDV, HAPT, and iBAC, and if possible adding a citation. I’m not sure simply mentioning them is worthwhile if no other information is given.

To improve the argumentation and the readability of the introduction of the paper based on your comments, the text has been changed and partly rearranged from line 35 to 79. In addition, I added a reference to the financial support section in line 64 which holds all necessary information on the mentioned research projects.

*To avoid such wear promoting operating conditions it is suggested to incorporate larger movements with  $\vartheta > \vartheta_{crit}$  to redistribute the grease on the raceways and therefore relubricate the contact areas to prevent starvation. These movements are often referred to as lubrication runs. Tests on small scale bearings showed that interrupting oscillating and wear critical movements with lubrication runs effectively prevents wear. This was even tested and verified for real-scale blade bearings with about 5 m diameter (Stammler (2020), Behnke and Schleich (2022)). In general, two different types of lubrication runs can be differentiated. First, lubrication runs can be the result of the pitch controller reacting to changing wind conditions by driving large pitch angle changes. This case can be considered as a random or stochastic lubrication run as part of the normal operation of the wind turbine. The second type would be an on-demand or scheduled lubrication run. In this case the change of the pitch angle of the wind turbine will lead to additional changes of the operation point and loads acting on the wind turbine. Therefore, the incorporation of additional, larger oscillation angles in the operation of the wind turbine is related to compromises between loads, energy yield and damage modes of the blade bearing and pitch systems (Schwack et al., 2018). As this compromise is hard to find because some damage modes like wear of blade bearings are still not completely understood, pitch controllers do not yet support on-demand lubrication-run strategies to the knowledge of the authors. However, pitch controllers of turbine manufacturers usually already execute simple and scheduled lubrication runs on a regular basis like once every 24 h to follow suggestions of the bearing manufacturers and to lower the risk of wear on the raceways. However, it is questionable if the time frame between those scheduled lubrication runs is small enough to prevent wear under any circumstances.*

*Stammler (2020) developed methods for evaluating load time series data regarding wear critical oscillations. Load time series data usually consist of continuous intervals of about 600 s which is too short to accumulate wear-critical operation conditions which provoke wear. Considering that the rotational speed of the turbine determines the number of oscillations in a specific time frame, it is conceivable that wear-critical operation conditions will form over hours and days which will be called medium-term behavior in the following. To mitigate this disadvantage of load time series data, Stammler (2020) uses a generic stitching approach for wear influencing operating conditions consisting of critical and beneficial sequences of pitch activity in order to develop a test program for wear of blade bearings. The aim of the test program proposed by Stammler (2020) is to replicate all wear critical operation conditions occurring over the turbine lifetime. The order of occurrence of the critical and beneficial sequences of oscillations in his test program is based on seasonal variation in the mean wind speed (long-term). Due to the nature of the compilation of beneficial and critical sequences the test program probably does not directly reflect medium-term real-world wind turbine operation. Starved*

*contact lubrication conditions especially can occur under oscillating operating conditions like in blade bearings (Wandel et al. (2022)). While the Hertzian contact travels over the raceway in an oscillating movement pattern, the lubricant which separates the contact partners is pushed out of the contact area and out of the contact track. This phenomenon has been under intensive investigation in the research projects like HBDV, HAPT and iBAC (see financial support section).*

*Behnke and Schleich (2022) list different publications with respect to wear dedicated test programs and the amount of cycles in several tests. Usually, numbers of about 40,000 oscillations with generic amplitudes and frequencies are tested to investigate wear as a failure mode. However, it is rather unlikely for a wind turbine to accumulate 40,000 wear critical cycles without changing the mean angle, frequency, or amplitude and hence to not include wear preventing cycles. Therefore, Schwack et al. (2022) also looked into wind conditions and load time series data and found out that worst case operation conditions are able to accumulate well above 13,000 wear critical oscillation cycles. They then conducted tests with 13,000 cycles, but were limited to consider variations in amplitudes, frequency, or mean values in the tests. Stammler et al. (2019) performed several tests on angular contact ball bearings of type 7220 to show the influence of random movement pattern variations and the effectiveness of lubrication-runs in terms of protecting the bearings from wear. However, being the first investigation showing oscillation angle variations and the effectiveness of lubrication-runs, the work does not answer the question to what extent and in what order protection runs and wear critical cycles can be found in real world wind turbine operation.*

*The present study uses the same wind data used in Schwack et al. (2022) in combination with an aeroelastic model of the IWT-7.5-164 reference wind turbine to obtain a better understanding on worst-case operating conditions with respect to wear of blade bearings. The proposed test program focuses on rather short time frames of less than 24 h and a pitch controller which does not include on-demand or scheduled lubrication runs to analyze the risk of wear damage of the pitch bearings under normal operating conditions which have a limited probability to lead to stochastic lubrication runs. It intends to show that it is possible to accumulate wear critical operating conditions during normal operation in a rather short amount of time. The novelty of the approach presented in this paper is the consideration of the order of occurrence of measured wind conditions and of simulated operating conditions.*

- 2.1 Wind data characterization: The colors in Figure 1 (bottom) were a bit hard to sort out. I might suggest that because the Weibull distribution fit is not mentioned in the text, it can be removed from the figure – or do the listed a and b values quantify that the measured wind speeds “do not correlate well with any of the IEC wind classes”?

I changed the colors and appearance of the bars to be translucent to improve the visual impression. The fit of the Weibull distribution in general shall help to see the differences of the standard IEC classes. The shape parameters are given for the sake of completeness and can be used for a more detailed comparison of site characteristics and IEC wind classes. However, this level of detail is not needed for the argumentation within this paper.

- 2.2 Wind data and turbine operation conditions: I had difficulty in following the descriptions in this section. At first, I thought this section was intended to describe the process by which wear-critical operations are determined, but then the first sentence in Section 3 says that is the point of Section 3. I think Section 2.2 maybe just gives an example of a particular interesting/likely to induce wear condition, but it's probably longer and more convoluted than needed at several pages and 3 figures.

Section 2.2 describes the fundamental assumptions and the methodology of looking at the measured wind data to define the critical sequence of wind conditions. Hence, your first thought is correct. As this

an essential step, I think the level of detail is appropriate. Section 3 uses the output of the described analysis as an input for running simulations which aim at closing the gap between wind measurements and turbine reaction like loads and pitch movement.

- 4.1 General description of the test program and simulation results: I think some of my confusion about Section 2.2 is not surprising, as the first sentence in Section 4.1 says “To evaluate if the critical sequence described in Chapter 2 is in fact critical in terms of wear..” That is, what is the difference between “critical sequence” and “critical (sequence) in terms of wear”? I found the process description and Figures 10 and 11 helpful here – it just felt like it took a long time to get to this point.

The wording in lines 199 – 200 has been changed for more precise description and to be more in line with the process described in Figure 10:

*A test program has been developed based on the critical sequence of wind conditions and using the simulation results of Chapter 3.*

- 6 Discussion and 7 Conclusions: The statement in 6 “While the test results of type 7220 bearings and real size blade bearings of type 51818 show almost similar results, the results from the scaled blade bearings of type 13229 and the real size blade bearings of type 12480 are different” seems to conflict with the statement in 7 that “Despite the differences in size and bearing design, the test program leads to comparable wear damages on the raceways.”

Thanks for pointing this out. The statement in the conclusions section has been slightly changed by deleting the adjective comparable.

*Despite the differences in size and bearing design, the test program leads to wear damages on the raceways. However, ...*

- 6 Discussion and 7 Conclusions: In 7 Conclusions and to my earlier questions about the importance (or not) of “site-specific” conditions to pitch bearing wear, where it is stated in the first sentence on line 515 that “...wear...can occur quickly under certain operating conditions...” I do agree that this has been shown but more than anything what I do not have a clear picture of is exactly what “certain” means here. What exactly are the characteristics that lead to wear? Can we say, or is every site a snowflake? I take it the IPC characteristics and maybe the turbulence and/or shear are the most important things? Or maybe the main point is that the article proposes a process by which a particular set of characteristics can be assessed for a given turbine/controller/bearing, but then again leads me back to the thinking that every site is a snowflake. That is, the characteristics of any given site must be known and then tested to see the extent to which wear may result and then the IPC potentially changed, which is implied where it says “It can be adapted to other turbine and controller designs as well as to other site-specific wind conditions.”

I added a sentence describing the “certain” operating conditions for more comprehensive read of the conclusions section:

*The medium-term, critical sequence of wind conditions characterized by very minor changes in the wind speeds, low turbulence intensity and high shear leads to pitch movements without much variation in oscillation amplitude and frequency and thousands of cycles without being interrupted by effective lubrication runs. The hypothesis that wear in blade bearings can occur quickly under these operating conditions was proven through testing of blade bearings, using a program based on site-specific and measured wind conditions, on both scaled and actual size bearing types.*

In general, you are right with the snowflake theory. Another site could potentially have even more critical wind conditions. The opposite is also possible, and the wear risk can be lower. However, the paper shows that some simple assumptions on potentially wear triggering operating conditions hold true. Hence, the findings can be used for developing test programs which can be used to assess or validate the risk of wear for a given system based on controller, turbine, bearing, lubricant, and site characteristics. In addition, the validated assumptions with respect to wear critical operating conditions can be used to develop more general and universal means for rating the wear risk in the design process or to develop on-demand lubrication run strategies.