Friction torque of wind-turbine pitch bearings – comparison of experimental results with available models

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Consolidated reply to review comments

1 Description

All reviewer comments are in *italic* letters, the reply of the authors is given directly below each comment. Text taken from the revised paper is in **grey bold** letters. The comments or put into sections according to topics / types of the comments. The following comments are all comments given by the reviewers. Each comment has been answered and several changes have been made to the manuscript.

2 Torque measurement system

The friction torque measurement system is described very briefly (line 5, page 3),despite its central importance for the presented work. There should be at least a figure showing conceptually the configuration of the pitch drive and the instrumentation .Corresponding text describing such a figure should also be added.

Torque measurement on shafts is a standard procedure for many applications and there are some commercial companies offering such systems. Torque measurements are available by the following companies (non-exclusive list):

KTR, Datum Electronics, Cedrat Technologies

Please refer especially to the following system, which was used in this test:
http://www.axon-systems.eu/products/1-channel-telemetry-systems-strain-gauge-temperature/axon-j1?lang=en

As these systems are widespread, a detailed explication in the paper seemed unnecessary. We did, however, add a few sentences on the principle, and a figure showing the orientation of the strain gauges on page 5:

The pitch drive is equipped with a strain-gauge torque measurement system at the pinion shaft on the low-speed side. A full bridge of strain gauges is mounted on the shaft (see Figure 3), together with a rotary unit. Data transfer and power supply is done telemetrically via a ring stator. The measurement system has been calibrated by applying known torques to the shaft.

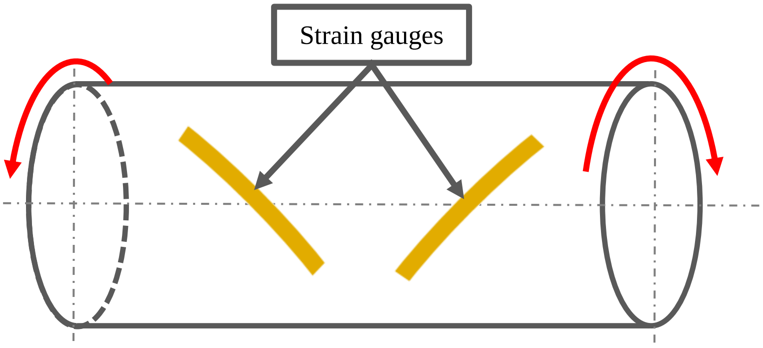

Figure 3: Torque measurement strain gauges on shaft.

3 Friction model results, calculation, normalization and discussion

Too little information regarding the application of the different friction models is given, in order to support the conclusion that all considered models are insufficient. The information given from line 10 on page 11 to the end of page 13 should be more thorough and be presented more systematically. It is also unclear how the roller element loads extracted from the FE model are used here. An example of a corresponding FE result would help here.

Normalizing with respect to the average torque measured at the maximum load, limits the scientific value of the presented data significantly. Since the measurements appear to be the main contribution of the model, either the absolute values should be provided, or data normalized with respect to a well defined quantity.

When they compare the measured friction torque value to the calculated values with four models,authors should give the parameter values and select reasons for these models.

We have reordered the information in the following way: At first, the adaptions of empirical values are described. Second, the results of the single models are explained. We think this is more systematically than before, thanks for the remark. We also added some further explanations on single aspects of the results on pages 10, 11 and 12:

Figure 7 shows the results of friction torque measurements at different rotating speeds of the pitch bearing. The measurements were executed with the bending moment varied in steps of 1 MNm. Figure 7 contains lines indicating values between 1MNm steps, these are interpolations. The external load was applied via a load frame (see Figure 2) and is expressed as the resulting bending moment at the blade root. The measurements for each load-speed-combination were repeated at least 20 times with no significant deviation between the mean values of friction torque. However, owing to the oscillating rotations used for the torque measurements, there is a relatively high standard deviation in the single measurements (shown for 2 and 5 MNm in Figure 7), due to torque vibrations caused by the repeated accelerations of the blade and pitch bearing masses.

The values of the friction torque are normalized to the highest value of the measurements obtained at 1.04 rpm and 6 MNm bending moment. For the conditions shown, the theoretical lubricant film thickness according to Dowson and Hamrock (Dowson and Hamrock, 1977) is close to or above the combined surface roughness of raceway and roller (Stammler and Poll, 2014). As the bearing is grease-lubricated, lubricant starvation might reduce the lubricant film thickness, thus a mixed lubrication regime is the most likely lubrication condition. The speeds examined are within the usual range of pitch bearing speeds. From the measured values, it is not possible to derive the speed dependence of the friction torque.

In Figure 8, the values are again normalized to the highest friction torque measured. The error bars refer to the standard deviation of the measured values.

In order to obtain results for the first manufacturer's and the PALMGREN calculations, previously unavailable empirical values had to be chosen to match the curves with the measured values: For the PALMGREN calculation, the value f_0 was adapted to fit the zero load condition and the value f_1 was adapted so that the difference between zero load torque and the highest load torque match the measured values. The first manufacturer's model includes all empirical values except the sealing friction of large slewing bearings. The empirical values provided with the model only include values for the sealing friction of bearings with a maximum diameter of 340 mm. Thus, the K_{S1} value that is part of the sealing friction was set in such a way that the non-load friction matches the measured values for the non-load condition.

The aforementioned choices of empirical values come with some drawbacks: Currently, the PALMGREN model cannot be used to predict the friction torque of other pitch bearings as there are no available values for the empirical factors f_0 and f_1. It is unclear whether the values used in this work are correct for loads higher than the measured loads or other bearing diameters. f_1 was adapted to match the slope between 0 and 6 MNm external load; if it had been adapted to the slope between 2 and 4 MNm, the differences between measurements and model calculations would have been higher.

Similar to the PALMGREN model, the first manufacturer model contains only one empirical factor, which can be adjusted (K_{S1} which is part of the M_{seal} calculation). In order to achieve a match, the value had to be raised drastically

compared to values for much smaller bearing diameters. Looking at the individual elements of the model, the adjusted M_{seal} is by far the largest part of the calculated friction at zero load and makes up nearly 99% of the friction at 2 MNm, which does not seem plausible. Additionally, the load dependence of the friction torque is underestimated by 67 % in comparison to the measurements. This may be caused by the M_{seal} part as well, due to the fact that a four-point bearing suffers relatively large deformations of the bearing rings under loads and should exhibit a load-dependent behavior of the sealing friction.

The WANG and the second manufacturer model contain all necessary empirical values. Yet, the results are not completely satisfactory: The second manufacturer's equation is explicitly not intended for zero load; as such this value is not displayed in the chart. The friction torque calculated with this model deviates by 35% from the measured values at a load of 2 MNm, and by 10% at a load of 6 MNm. As the slope of the load dependence of the calculated curve is 15% higher than that of the measured values, it might result in overestimated friction torques at loads higher than 6 MNm.

The model proposed by WANG does not take account of the sealing friction and shows the friction torque to have a rather high speed dependence that does not match the measured values. The model was originally intended for the calculation of friction under fully lubricated conditions and needs some further adjustments for mixed friction conditions.

Fehler! Verweisquelle konnte nicht gefunden werden. **shows the speed dependence of the different calculation methods and the measurement results at 5 MNm external load. While the measurement values and most of the model calculations show either no speed dependence or the speed dependence depending on revolutions per minute (which does not lead to a drastic increase in the torque while the velocity of the rollers does rise due to the large diameters) , the model of WANG contains a dependence on roller speed.**

The measurement data used for this paper was created during a commercial project for a customer. This data is subject to non-disclosure agreements. As such, absolute values cannot be given within this paper. For this very same reason, we did not include the individual values of empirical factors for the single models, as this would allow for the calculation of the absolute values.

We deem the scientific results worthy nonetheless: The validity of the friction models for large slewing bearings has not yet been evaluated in any publication known to the authors. The lack of appropriate models for friction torque calculation of blade bearings has been clearly shown and the need for further research in this field was stated. Due to this, there is also a lack of a "well-defined quantity" to normalize the values against – there is simply no comparable data available in the literature.

3 Minor and practical comments

The term movement is in general too broad for a scientific text. In many places of the text the term can be replaced with more specific ones such as rotation and shearing.

Indeed, rotation is a more suitable expression in many of the cases. This has been changed.

In several places the subscript "ges" is used instead of the English equivalent "tot".

The initial idea was to maintain the original subscripts in order to make it easier to compare the equations mentioned in the paper against the ones in the references. But we understand the subscript "tot" is self-explanatory in an English paper and exchanged "ges" against "tot" in the remaining instances.

the argument in line 19 on page 10 is unclear

The argument was completed by an explanation:

However, owing to the oscillating movements used for the torque measurements, there is a relatively high standard deviation in the single measurements (shown for 2 and 5 MNm in Figure 6), due to torque vibrations caused by the repeated accelerations of the blade and pitch bearing masses.

"had to be chosen" (line 13, page 11)

Rectified.