Statistical analysis of fatigue loads in a direct drive wind turbine

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Abstract

The design calculation of a wind turbine typically involves a large number of simulations of wind turbine dynamics response. In order to assess the fatigue life of drive train components, we seek to determine how the component damage can be estimated, not only in terms of its expected value, but also its distribution accounting for randomness due to turbulent wind field. It was found that for assessing the fatigue life of main shaft bearings, a quasi-static drive train model may be sufficient for a direct drive concept. Also, it was observed that both the average and variability of the damage rate vary substantially with the mean wind speed. Therefore, in addition to the mean, also the variability of the estimated accumulated component damage should be considered.

Key words: Fatigue loads, bearings, certification analysis

1 Introduction

This contribution concerns the design of wind turbine drive trains, in particular with respect to fatigue calculation. What is here discussed is the prediction of the fatigue life of a particular turbine, based on a simulation model of the turbine (i.e. in the design phase) in contrast to other methods based on statistical analysis of a population of turbines from fault and operation data, as exemplified by [7].

In the design process of modern multi-MW wind turbines, there is a large set of simulations to be carried out, both with respect to extreme load cases (ultimate load cases) as well as with respect to fatigue calculations of e.g. blades, cyclic bending of main shaft, bearings, in normal operation. Such load cases are defined in international standards (e.g. IEC-61400 [2]) and standards form certification bodies (e.g. [3]). One method for evaluating the fatigue life of the drive train components is based on evaluating a fixed number of simulations (with random realizations of the turbulent wind field) for each integer mean wind speed that from which the amount of accumulated damage is estimated, represented by a damage index. By adding the expected duration of the wind speeds at the (planned) site of the turbine (added by a number of events, such as start-up, parking, idle) the risk of failure in a certain turbine component can be assessed.

However (apart from the assumption that the damage can be commutatively added), this method only computes the expected value of the accumulated damage, and the variability is compensated by choosing a suitable safety margin. As an additional level of uncertainty, the fidelity of the drive train model will introduce an error in the result that should be small compared to the loading variability due to wind loads.

In the present contribution we seek by means of Monte-Carlo simulations to (1) understand how the drive train model detail can affect the predicted damage index rate of main shaft bearings, (2) understand how the damage rate of main shaft bearings is distributed at different mean wind speeds, and (3), accounting for the wind speed distribution, find the distribution of accumulated bearing damage for the turbine design life.

2 Simulation of fatigue rate of main shaft bearings

As a basis for this investigation, we consider simulation model for a commercial multi-MW direct drive wind turbine which was implemented in the software ViDyn [1] developed by Teknikgruppen AB, that has been used for load calculations of real wind turbines. The model is a structural model of the full turbine, including a realistic control system (individual pitch control), that is subjected to a 3-dimensional wind field. The wind loads are computed using Blade Element Momentum theory, implemented in code Aerforce [5]. The wind fields for a specific mean wind speed *v* are obtained from random realizations based on the Kaimal spectra as described in the standard IEC-61400 [2] characterized by turbulence intensity $I_{ref} = 0.14$ and wind shear with power law exponent 0.16. Each such wind field realization is used as input to the full-turbine model from which the forces at the hub are extracted.

Thus, the excitation from wind is represented by a 6-component time-series consisting of the 3D force vector (in xyz-direction) and 3D torque vector (around the same axes) acting on the hub. From a 10-minute simulation (all simulations below are of 10 min duration) at a specified mean wind speed, the time-history of forces acting on the main shaft bearings are computed, from which a mean damage rate is determined from standard bearing fatigue calculation. With the aim to consider different drive train models fidelity, a direct drive turbine model is considered as in Figure 1. The main shaft is represented by a rotating Euler-Bernoulli beam (gyroscopic and centrifugal terms considered in the equations of motion), added with point inertias representing hub and generator rotor in a rotating coordinate system, supported by linear springs representing flexibility in bearings and bearings mounts. The weight of the stator is carried by the main shaft via bearings (also represented by linear springs), while the torque support between the generator stator and the bedplate is represented by a torsional spring. In the drive train model, the bedplate is assumed to be fixed.

The rate of bearing fatigue is estimated at four bearings along the main shaft; Front and Rear main bearings and Front and Rear generator stator bearings. Given a time-history of bearing forces, the damage index rate is computed using the Palmgren-Miner rule as

$$DI = \frac{1}{T_{\text{sim}}} \sum_{i=1}^{N^{rev}} \frac{1}{L_i} \qquad L_i = \underbrace{a_1 a_2}_{=1} a_3(P_i) \left(\frac{C}{P_i}\right)^p \tag{1}$$

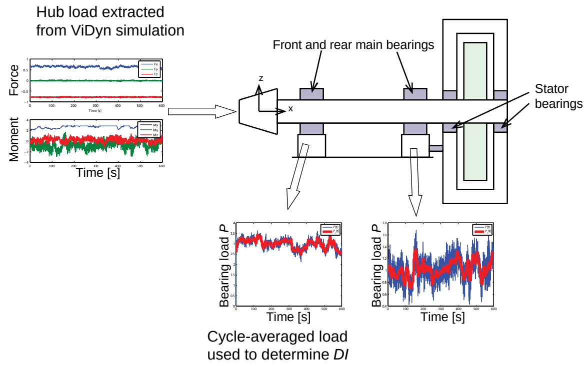

Figure 1: Drive train simulation setup.

where T_{sim} is the simulation time (600 s), N^{rev} is the number of revolutions during the simulation, L_i is the L_{10} - life associated with equivalent load $P_i = aF_a + bF_r$ obtained from the bearing-specific combination of axial and radial forces and a, b, a_1, a_2, C, p are parameters, and $a_3(\cdot)$ is a function specified by the bearing design, cf. [4]. It should be noted that this is a rather crude model of bearing life, and does not consider the many different mechanisms that may lead to bearing failure, cf. [6].

3 Results

A number of realizations of the wind field each followed by a deterministic model simulation carried out to estimate the variability of bearing damage index rate, and how this rate varies with mean wind speed. The variability is studied with respect to drive train model detail.

Hence, we consider the problem of analysis as follows: For given wind field (input), we may compute the damage index rate *DI* for four different bearings (outputs). Then, how can the model detail affect the outputs? And how does the output depend (in terms of mean and variance) on the mean wind speed?

3.1 Model fidelity

A comparison has been made regarding the influence of modeling detail. Three choices of model detail are here considered with respect to the distribution of damage index rate. In the complete model, the inertia and gyroscopic terms are considered in the equations of motion. A simplified model could be considered since a direct drive the main shaft operates under relatively modest speed, 5-15 rpm, the centrifugal and gyroscopic terms in the equations of motions could possibly be ignored. Finally the quasi-static condition is considered, i.e. all inertia effects are ignored. From a computational point of view, by simplifying the equation of motion, in particular if the quasi-static model is sufficient, would greatly reduce the simulation time.

A comparison of the front and rear main bearings for the mean wind speed 10 m/s is shown in Figures 2-3, where it can be concluded that a quasi-static drive train model is sufficient to predict damage rate for those bearings. In contrast, as shown in Figures 4-5, inertia effects (but not necessarily gyroscopic and centrifugal effects) should be considered to predict the damage index rate of the stator bearings. The same conclusion holds for all studied mean wind speeds.

A sometimes adopted model simplification is to lump together the generator rotor and stator as one point inertia. It was numerically found that the damage index rate on the main bearings was unaffected of this simplification, (cf Figure 2-3), which appears reasonable since the forces affecting the main bearings are essentially quasi-static. In such case, the stator bearings must be investigated separately.

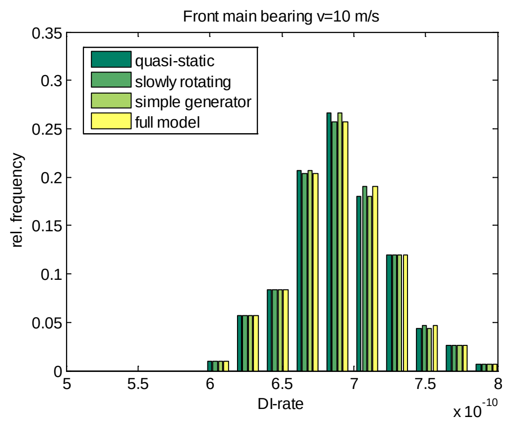

Figure 2: For front main bearing, damage rate (Eqn. 1) for mean wind speed 10 m/s, 300 realizations comparison of four drive train model details. Damage index rate distribution appears independent of model.

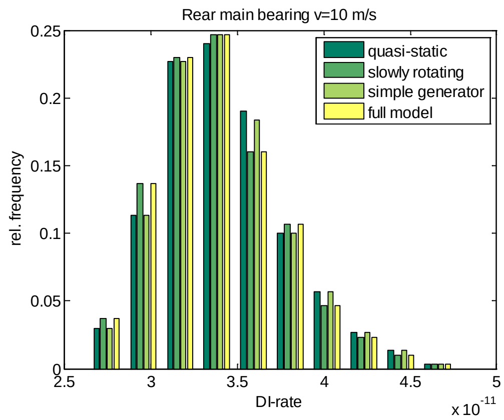

Figure 3: For rear main bearing, damage rate for mean wind speed 10 m/s, 300 realizations comparison of four drive train model details. Damage index rate distribution appears independent of model.

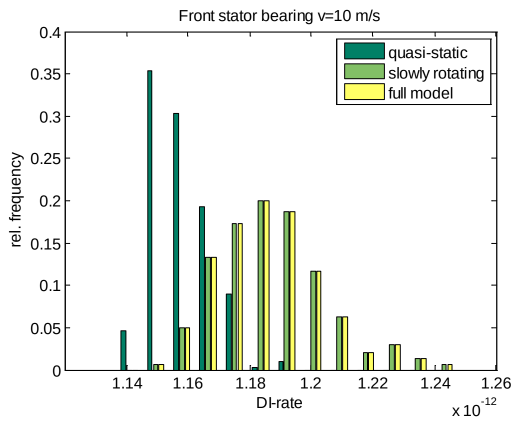

Figure 4: For front stator bearing, damage rate for mean wind speed 10 m/s, 300 realizations comparison of three drive train model details. The quasi-static model assumption strongly affects damage index rate distribution.

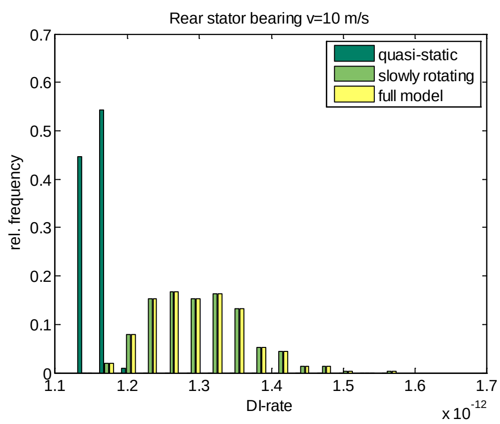

Figure 5: For rear stator bearing, damage rate for mean wind speed 10 m/s, 300 realizations comparison of three drive train model details.

3.2 Mapping of damage rate

For simulations at different mean wind speed (4,7,9,10,11,13,15,17,20,23,25,26,27,28 m/s) with varying number of realizations, (30,250, 250 300,500,500,343,300,925,60,30,287,30,30 respectively, the number of realizations determined by available CPU-time and disk space), the damage index rate for the front and rear main bearing collected in histograms are shown in Figures 6-7. For the front main bearing, it is seen that the largest damage index rate, as well as the largest variability arise at 11 m/s, which is the region where rotor blade pitch control starts, which reduces the axial thrust load, and thereby the equivalent load *P*. For the rear main bearing, the mean damage index rate and variability increase for increased mean wind speed, Figure 7. The front and rear generator stator bearings give very similar results, as shown in Figures 8-9. Here the largest rate is for high wind speed. The very large spread at high wind speeds as observed in all but the front main bearing is likely due to the inertia of the generator combined with increased tower motions affecting mainly the rear bearings.

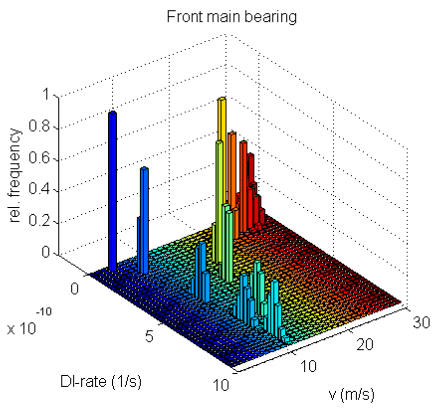

Figure 6: Histogram of damage index rate for front main bearing at different mean wind speeds.

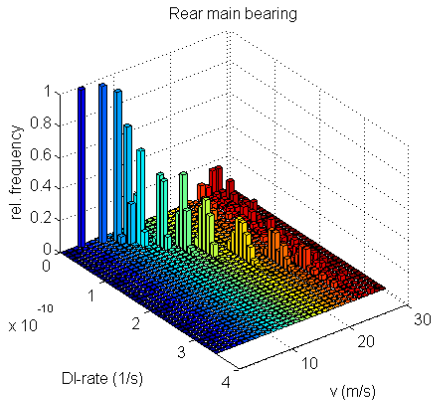

Figure 7: Histogram of damage index rate for rear main bearing at different mean wind speeds.

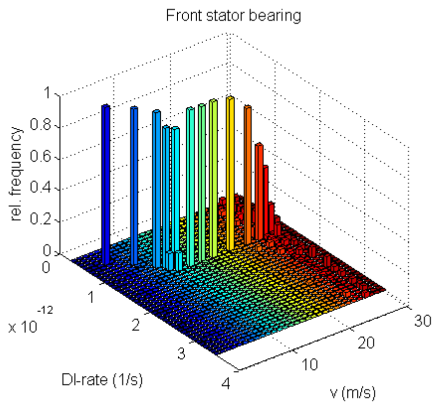

Figure 8: Histogram of damage index rate for front stator bearing at different mean wind speeds.

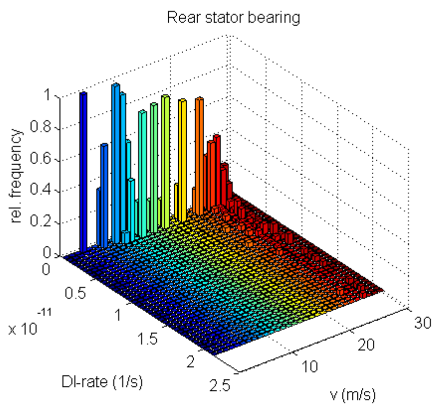

Figure 9: Histogram of damage index rate for rear stator bearing at different mean wind speeds.

4 Accounting for wind speed distribution

To assess the total damage in bearings (or other components) over a T_{tot}= 20 year operation, the damage index rate DI^k (*k* being the identifier of the specific component considered) should be integrated over the service life.

$$DI_{tot}^k = \int_0^{T_{tot}} DI^k(t)\mathrm{d}t, \quad (2)$$

Since the wind load is in fact a stochastic process, the total damage accumulated over 20 years DI_{tot}^k could be described by some distribution function, from which mean, variance and probability that failure occurs can be determined (e.g. the probability that DI_{tot}^k >1 for the studied *k,* or if complete system reliability is considered, for any *k*). In this formulation, it is assumed that the damage rate also includes events such as start-up, parking, idle, stand-still etc.

By assuming that the damage is commutatively accumulated, and that the damage index rate can be determined by mean wind speeds, the total damage distribution can be obtained as

$$f(DI_{tot}^k) = \int_{v=0}^{v=\infty} f(DI^k(v))\mathcal{W}(v)\mathrm{d}v \quad (3)$$

where $f(\bullet)$ is the probability density function. In (3), the total damage rate is obtained by weighting the damage rate by the mean wind speed distribution *W(v)* (usually a Rayleigh or Weibull distribution for 10-min averages). However, due to cut-in speed, and that the normal operation ends at a certain max wind speed, the integral in (3) is essentially bounded by a lower value v_{min} and a higher value v_{max} , (in reality, the damage rate below v_{min} is in fact the damage rate under idle). In the following, we make the important simplification of considering only normal power production with clean airfoils in the range of v_{min}= 4 m/s and v_{max}= 28 m/s, hence we do not specifically consider start-up/shut-down, yaw misalignment, rough airfoils (e.g. due to icing), and stand-still, parked or idle conditions.

Remark

In the spirit of (3), a simple approach to determine the damage rate is to determine the damage rate at each integer wind speed within the range of operation, and by adding the expected duration of the wind speeds at the (planned) site of the turbine (added by a number of events, such as start-up, parking, idle) the total accumulated damage is obtained, which can be used to assess the risk of failure for that specific component, i.e.

$$E(DI_{tot}^k) = \sum_{i \in S} E(DI^k(v_i))T_i \quad (4)$$

Here in (4) DI_{tot}^k is the accumulated damage of component *k*, *S* is the set of all events, and T_i is the expected time-duration of event *i* over the course of planned life (20 years), which can be obtained as $T_i = T_{tot}W(v_i)$. □

Since the distribution of DI^k varies with different mean wind speed, the first issue at hand is the distribution of DI_{tot}^k (i.e. to evaluate Eqn (2)), and its related statistics; mean and variance. Since one would typically seek to determine the probability that DI_{tot}^k is below a certain value, also the cumulative distribution of DI_{tot}^k that is sought. However, a direct numerical evaluation of the integral (3) requires a very large set of realizations also at non-integer mean wind speeds as DI^k varies with mean wind speed *v*. From inspection of the distributions in Figs 6-9, a somewhat reasonable approximation is to consider the damage index rate as normally distributed (quite questionable at high mean wind speeds), with parameters μ and σ dependent on the mean wind speed *v*. By evaluating μ and σ for the mean wind speeds evaluated, and assuming that the parameters μ and σ varies linearly between the evaluated mean wind speeds, we obtain a numerically evaluated functional expression of the total damage index rate probability density function:

$$\begin{aligned} f(DI_{tot}^k) &= \int_{v_{min}}^{v_{max}} f(DI^k(v))\mathcal{W}(v)\mathrm{d}v \\ &\approx \int_{v_{min}}^{v_{max}} \mathcal{N}(\mu(v),\sigma(v))\mathcal{W}(v)\mathrm{d}v \end{aligned} \quad (5)$$

Evaluating (5) numerically, the probability density functions of DI_{tot}^k takes the form as shown in Figures 10-13. As can be seen, there is a quite significant variability, with a "tail" extending towards increasing damage index rate, indicating that the full variability of damage index rate should be considered, as there is a significant risk that the actual accumulated damage over 20 years exceeds safety factors based on multiplication of the mean estimated damage.

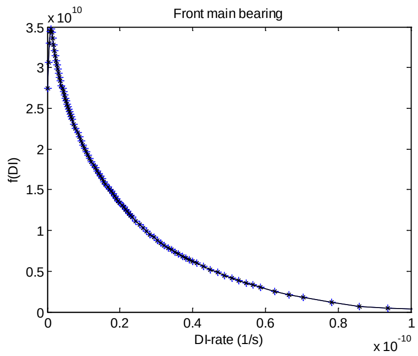

Figure 10: Distribution of total damage rate (Eqn. 5) for front main bearing.

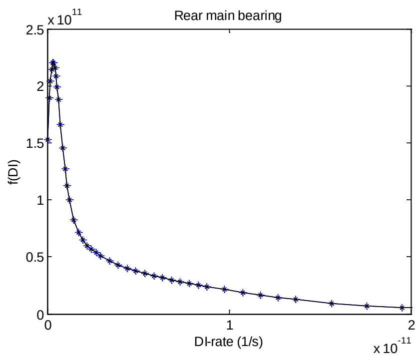

Figure 11: Distribution of total damage rate for rear main bearing.

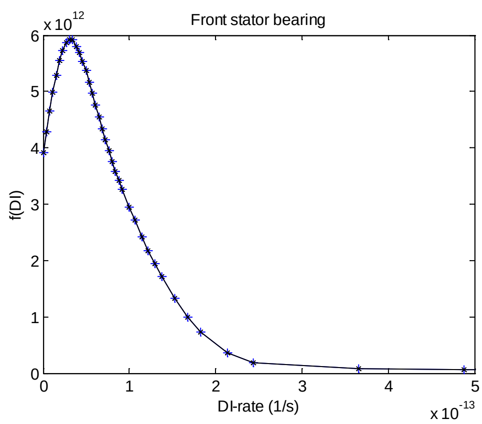

Figure 12: Distribution of total damage rate for front stator bearing.

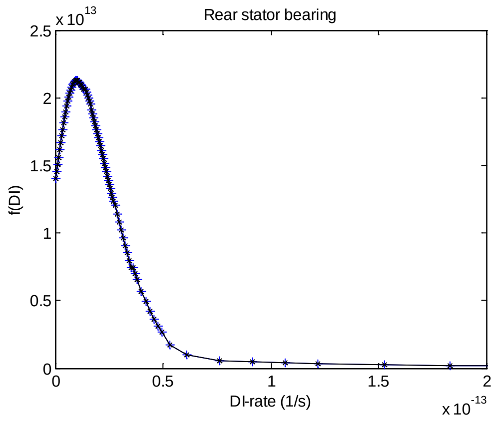

Figure 13: Distribution of total damage rate for rear stator bearing.

5 Conclusion and outlook

It was found that model detail can for some cases significantly affect the estimated damage rate, depending on the specific concept of turbine drive train. For the specific direct drive concept studied here, a quasi-static model was sufficient to predict the damage rate for the main bearings that carry the drive train weight and wind thrust load, whereas the stator bearings that carry the stator mass require inertia to be considered. It should be noted that these conclusions are based on drive train simulations entailing a "fixed" foundation (i.e. the tower and bedplate are rigid).

The main result of the present investigation was that the not only the mean, but also the variance of damage rate depends on mean wind speed, and that this carries over to the computed total damage index. An important future work is to investigate the generality of these conclusions with respect to other drive train designs.

Future work will be focused in more detail study the efficient sampling of wind turbine simulations to estimate mean and variability of predicted damage in the turbine drive train components with sufficient accuracy. Considering the front main bearing, it seems that wind speeds around start of pitching requires most attention, whereas for the rear main bearing it is not likewise obvious as high wind speeds are significantly less frequent.

Moreover, additional cases with respect to turbulence characteristics should be explored, as well as the other conditions (start-up and shut-downs, ice on blades, etc.). Following this, more elaborate wind models should be studied, in particular with respect to wakes in the wind field that may appear randomly in the swept area.

Here, the model of the drive train was decoupled from the full-turbine model. Therefore, a future important step is to include also the more elaborate model within the full-turbine analysis code, which would also allow for examining different turbine designs. However, this requires an essentially new simulation platform; one such is currently under development at our department (under the name FreeDyn).

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