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Investigation of the relationship between main-bearing loads and wind field characteristics

E Hart[1], A Turnbull[1], D McMillan[1], J Feuchtwang[1], E Golysheva[2] and R Elliott[2]

[1] Wind and Marine Energy Systems CDT, University of Strathclyde, Glasgow, UK
[2] Romax InSight, University of Nottingham Innovation Park, Nottingham, UK

E-mail: edward.hart@strath.ac.uk

Abstract. This paper investigates the relationship between main bearing loads and the characteristics of the incident wind field in which a wind turbine is operating. For a 2MW wind turbine model, fully aeroelastic multibody simulations are performed in 3D turbulent wind fields across the wind turbines operational envelope. Hub loads are extracted and then injected into a simplified drivetrain model of a single main-bearing configuration whose parameters are determined using finite element software. The main bearing reaction loads and load ratios from the simplified model are presented and analysed. The results indicate that there is a strong link between wind field characteristics and the loading experienced by a single main-bearing, with more damaging load ratios seen to occur in low turbulence and high shear wind conditions.

1. Introduction

Wind turbine main-bearings seldom reach their design lives of roughly 20 years, with many failing in less than six [1]. The reasons for this are multi-faceted and as yet not fully understood; certainly the conditions experienced by the main-bearing inside a wind turbine drivetrain deviate significantly from the well understood and relatively constant conditions present in conventional energy plant generators. It is in these latter and altogether more hospitable conditions where much of the current main-bearing knowledge base has been developed and, when dealing with wind turbines, there is generally an implicit assumption that this prior experience can be reapplied without much alteration. The relatively high proportions of main bearing failures seen in the field suggest that these assumptions need to be revisited. This paper seeks to both challenge these assumptions and attempt to shed some light on the problem by addressing the following question:

What range of load conditions are experienced by a wind turbine main-bearing across its operating envelope and to what extent can these load conditions be linked to characteristics of the incident wind field?

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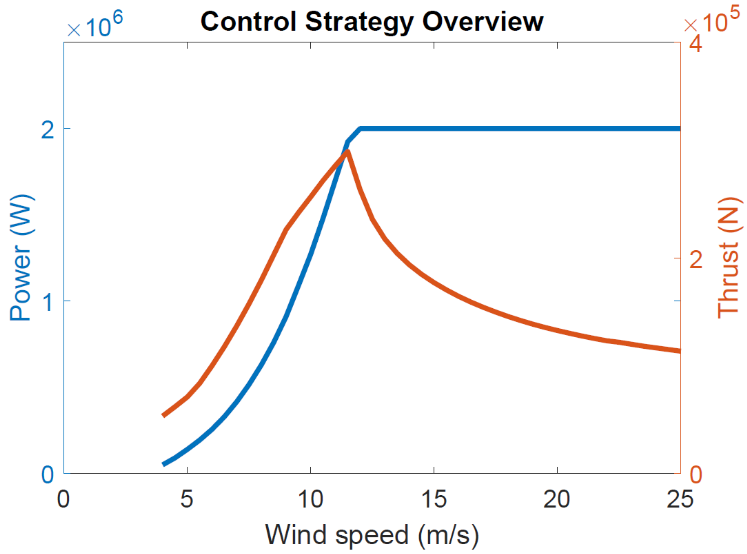

Figure 1. Design power and thrust curves for the simulated wind turbine.

2. Methodology

The current paper focuses on the case of a single main-bearing. The two main-bearing case will be considered in future work.

The investigations proceeded in three distinct stages:

(i) Generation of 3D turbulent wind fields and fully aeroelastic simulations of complete wind turbine system

(ii) Extraction of hub loads from simulations and injection into simplified drivetrain model

(iii) Analysis of main-bearing reaction forces obtained from simplified drivetrain model.

Fully aeroelastic multi-body simulations of a 2MW wind turbine were performed in GH Bladed software and the 3D wind fields generated in compliance with IEC standards [4] using a Kaimal spectrum. The wind fields used in this case were generated as in [5] where the relevant theory is also discussed. As a brief summary: the second order wind field statistics are captured in frequency space by what is known as a spectral tensor, a function of wavenumer whose values are related to the energy in the wind. For a given spectral tensor model (the Kaimal spectrum being one) velocity components can be determined via summing a set of coefficients, determined for that wind model, each multiplied by unit variance random numbers. The presence of random numbers means that, using different initial random number seeds, it is possible to generate wind fields which are different, but share the same second order statistics. Summary data for the wind turbine model is given in Table 1 and its design power and thrust curves are given in Figure 1. Figure 2 shows a schematic of the drivetrain model, including the reference frame used. Forces along a given axis, i say, will be denoted by B_i for input forces and F_i for bearing reaction forces, and similarly moments will be denoted by M_i. In order to obtain an understanding of the loads experienced by the main bearing, we treat the main bearing as a simple support. The hub loads are then decomposed into their orthogonal components and in-plane force-moment pairs injected into models of the form shown in Figure 3. For example, M_z and B_y will be injected into the same model. The bearing is assumed to react all of the thrust forces. The length L_1 is the distance (supplied by Romax) from the hub to the main-bearing on a commercially available wind turbine of the same size as the simulated model. The length L_2 is determined by Romax finite element software to be the equivalent length of the torque arm from the main-bearing to

Table 1. Data for simulated wind turbine.

Rated power	2MW
Rotor diameter	80m
Blade number	3
Hub height	61.5m
Aerodynamic control	Pitch
Fixed/Variable speed	Variable
Controller	PI

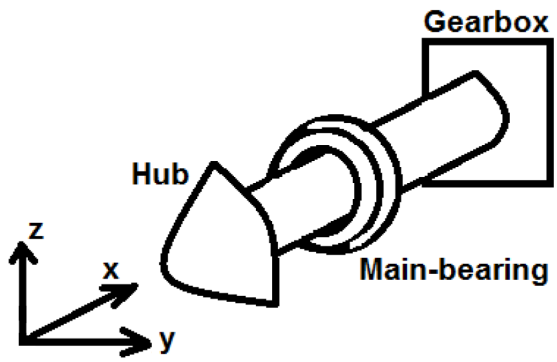

Figure 2. Drivetrain configuration, including reference frame.

the gearbox. Gearbox spring stiffnesses are also available, however, the current analysis has been performed in static equilibrium and since the system is determinate, these have not yet been required. The outputs from these simplified models is then re-combined, giving approximations of the resultant reaction forces on the main bearing. The main outputs investigated in this work are the axial to radial load ratio (F_x/F_R where $F_R = \sqrt{F_y^2 + F_z^2}$) and peak loading in both the axial and radial planes. The load ratio has been found to be important for bearing health, since high values of F_x/F_R can lead to damage modes related to skewing, sliding and the unseating of the bearing row [2, 3].

Simulations were performed in GH Bladed software for the wind turbine model outlined above. IEC design requirements were followed throughout the simulations [4]. The process and analysis followed here closely resembles that of [5]. 6 different 3D turbulent wind fields were generated for each combination of: mean wind speed (10, 12, 16, 20 m/s), turbulence intensity (TI) (low, med and high as specified by the IEC [4]) and power law shear exponent (0.2, 0.6); a total of 144 wind fields. The turbine was simulated in each of the generated wind fields and the hub loading, which includes gravitational and inertial forces, was extracted. Each of these simulations resulted in 10 minutes of hub loading time history.

3. Results

Figure 4 show a histogram of the axial to radial bearing reaction load ratios, F_x/F_R, for 10m/s mean wind speeds, medium turbulence intensity and both low and high shear exponents. It

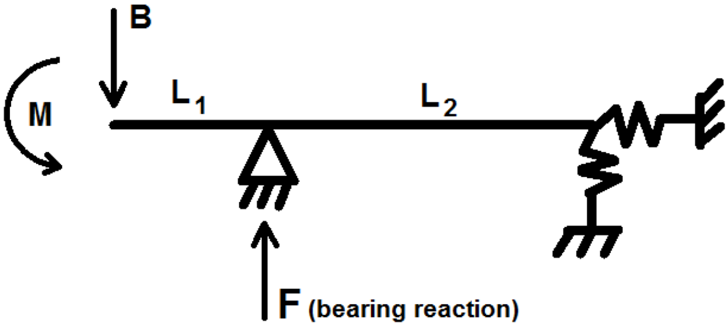

Figure 3. Simplified drivetrain model for each in-plane force-moment pair.

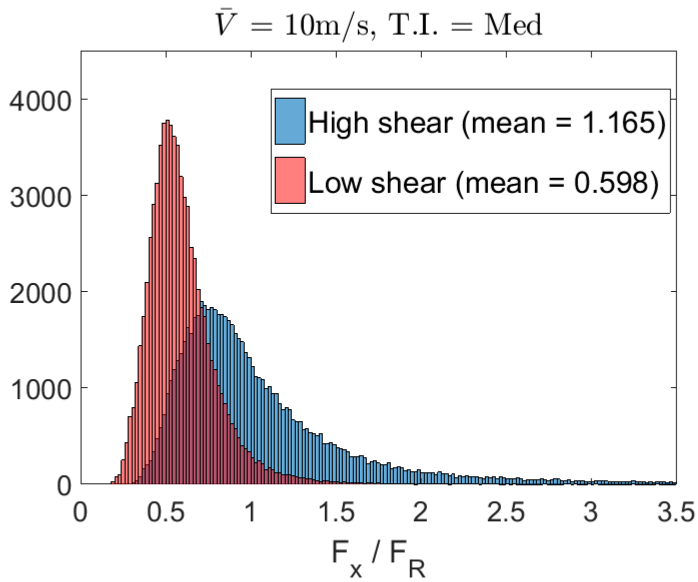

Figure 4. Histogram of axial to radial bearing reaction force ratios across simulations with a mean wind speed of 10m/s, medium turbulence intensity and low (0.2) and high (0.6) shear exponents.

can be seen that the load ratios have a distribution which is Weibull in nature. An increase in shear profile has a significant effect, resulting in a marked shift of the mean towards higher load ratio values. It was found that all of these plots at various mean wind speeds and turbulence intensities were qualitatively similar, hence, it is the position of the mean values which is of most interest in order to make comparisons. Figure 5 shows the values of these mean main-bearing load ratios across the whole simulation range. There are two very clear results which can be seen in this plot. The first being that shear exponent is the single most important factor in determining the mean load ratio for the main bearing reaction forces. The second is that there is noticeably different reaction behaviour between regions where pitch control is active and regions where it is not, the transition between these two regimes is captured by the high shear and high turbulence intensity point with 12 m/s mean wind speed. Furthermore, in general the mean load ratios experienced by the main-bearing are not sensitive to the turbulence intensity, except in the pitch active regions (16 and 20 m/s) and with the high shear exponent. It is of particular note that for the above rated operational region, where pitch is active, the highest mean load

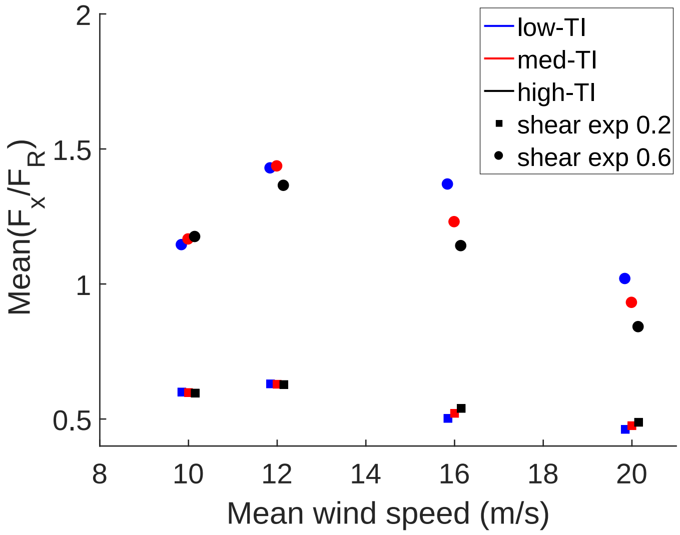

Figure 5. Mean axial to radial load ratios. Note, results have been staggered about each mean wind speed for clarity.

ratios (and so potentially most damaging in terms of bearing misalignment) are experienced in high shear and low turbulence intensity conditions.

Peak reaction loads on the main-bearing in both the axial and radial directions are also important drivers of mainbearing lifetime. In order to investigate these, peak axial and radial loads were found from each main-bearing reaction time history generated using the drive-train model. The means and standard deviations of peak loads across the six wind fields for each wind field type are shown in Figures 6 and 7 for radial and axial loads respectively. Peak radial loads can be seen to generally increase steadily with mean wind speed and the main driver for changes is again the shear exponent. It is important to note that increasing the shear exponent results in a decrease in the peak radial loads, this make intuitive sense since increased imbalance in the rotor is acting contrary to gravitational forces, thus canceling out some loading. The peak radial loads are clustered fairly tightly and have small enough standard deviation, especially at lower wind speeds, to imply that the loads are strongly linked to wind field characteristics.

Peak axial loads on the other hand generally decrease with mean wind speed, as should be expected from the thrust curve in Figure 1, and the association to shear exponent is much less marked. Instead, it can be seen here that the main driver for peak axial loading is the turbulence intensity. Again it can be seen that the loads experienced by the main bearing are closely linked to the wind conditions in which the wind turbine is operating. Finally it can be seen that the results in Figure 5 cannot be inferred from the peak loading trends seen in Figures 6 and 7, since ratios here remain more or less in the same proportions, and this implies that there is some other coupling between these two loads which is dynamic in nature and cannot be reconstructed from extreme values alone.

4. Conclusions

The results seen here imply the following:

(i) There is a strong link between the forces experienced by a single main-bearing and the wind conditions in which the wind turbine is operating

(ii) Load ratios on the main bearing behave very differently in above and below rated operation,

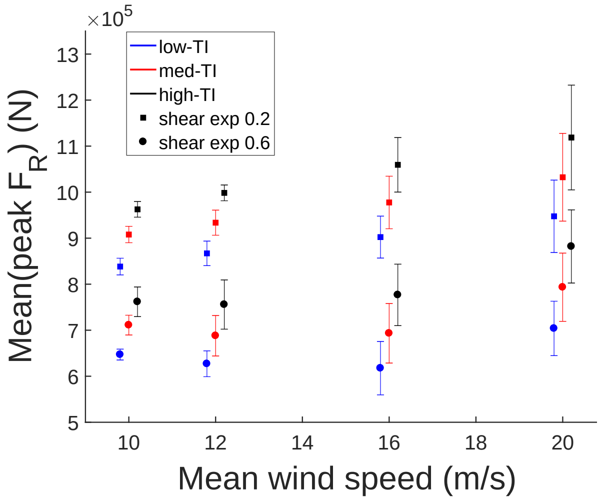

Figure 6. Mean peak radial loading over each set of six wind fields with parameters in common. Note, results have been staggered about each mean wind speed for clarity.

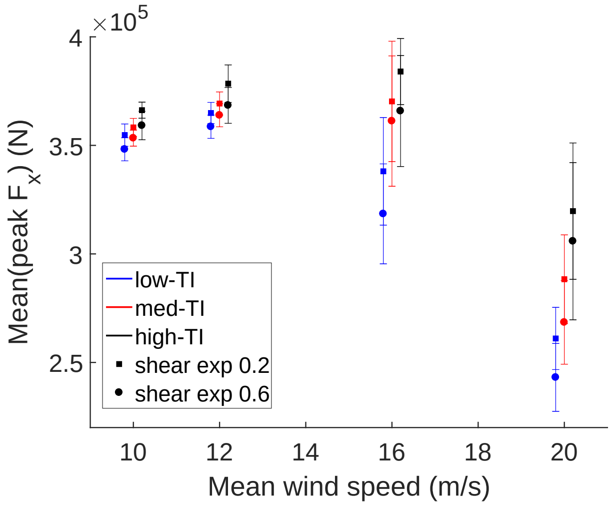

Figure 7. Mean peak axial loading over each set of six wind fields with parameters in common. Note, results have been staggered about each mean wind speed for clarity.

with the most damaging conditions occuring in low turbulence intensity and high shear across most wind speeds

(iii) Load ratios on the main bearing are most strongly driven by shear exponent in general, this is also the case for peak radial loading

(iv) Peak axial loading at a given mean wind speed is most strongly driven by turbulence intensity.

The results documented here also demonstrate the very variable nature of main bearing loads across the operating envelope of a wind turbine. This challenges the assumption that knowledge from more conventional power generation technologies can be reapplied in this case with little or no alteration. The result of doing this might well be contributing to main bearing failures.

There was seen to be strong links between the loads experienced by a single-main bearing and the characteristics of the incident wind field. This implies that effective health monitoring techniques for main-bearings may necessarily include wind field measurements and analysis.

Acknowledgements
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