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A comparison study of the two-bladed partial pitch turbine during normal operation and an extreme gust conditions

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Abstract. This paper shows the load comparisons between the numerical simulation and the full-scale load measurement data. First part of this paper includes the comparisons of statistic load in terms of maximum, mean, and minimum values for the selected normal operation cases. The blade root bending moments and tower top bending moments are compared. Second part of this paper introduces the dynamic response comparisons during an extreme wind gust condition where the wind speed changed approximately 10m/s during three seconds. The rotor speed and blade root flapwise and edgewise bending moment are compared. The nonlinear aeroelastic simulation code HAWC2 is used for the simulations. A very fine agreement between the simulated and the full-scale measured loads is seen for the both comparisons.

1. Introduction

The question of best cost efficiency between two- and three-bladed turbines for the offshore application has been recently brought up by Envision. Envision builds a new 3.6MW size of two-bladed offshore wind turbine with partial pitched blade concept, called PP-2B. A prototype of the turbine has been erected at Thyborøn in Denmark where it has been tested since 2012 September. The validation of the structural integrity of the wind turbine structure involves both analysis of fatigue loading as well as extreme loading. With the trend of persistently larger turbines, the extreme loading seems to increase relatively in importance. The extreme loading to be assessed in an ultimate limit state analysis, is based on a number of extreme load cases – examples are a storm situation, an extreme (short term) wind shear, extreme wind speed gusts and extreme wind direction gusts. It is common practice to estimate extreme wind turbine loads based on load events specified in numerical simulation codes. However, the gust events described in the codes are formulated as coherent gusts of an inherent deterministic character, whereas the gusts experienced in real situation are of a stochastic nature with a limited spatial extension. This conceptual difference may cause substantial differences in the load response of a wind turbine, when a gust event is imposed. Recently, one extreme gust situation was detected at the met mast at 24 October 2013 on the test site. There was a mean wind speed at hub height of 17.8 m/s and the wind speed jumped from 13.6 to 23.3 m/s during 3sec. The wind direction is simultaneously changed about 30deg within 10sec. In order to introduce more realistic extreme load situations of such stochastic nature, a very versatile theory for simulation of Gaussian turbulence driven gust situations has previously been developed [1, 2]. The theory provides generation of consistent synthetic turbulence fields, consisting of fully 3D multiple correlated stochastic processes, containing one or more extreme events, with the second order structure functions correctly represented.

One of the extreme cases, a 50 year recurrence extreme wind speed case at standstill condition (DLC 6.1), has previously been studied by the authors [3]. From this study the suggested PP-2B design could in itself reduce extreme loads in storm situations up to 60% compared with the three-bladed wind turbine, when the rotor during side wind aligns in a horizontal T-configuration and yawed 90deg in relation to the wind direction. In the present paper another extreme case, an extreme gust, is investigated with the measured wind gust from nature. The statistic loads, min-mean-max loads, during normal operation condition for inner and outer blade bending moment and tower top bending moments are compared between the measurement and the simulation.

2. Model description

The two-bladed partial pitch concept was introduced by Envision. It has two blade parts referred to as the inner and outer part. The inner part is designed for passive stall control while the outer part is designed and operated for pitch regulation. A pitch bearing is placed at the end of the inner part of the blade which is located 20*m* from the hub. This turbine has been erected and tested at Thyborøn in Denmark since September 2012 (see Figure 1). First of all the selection of full-scale measurement load data will is discussed in this section. Secondly, an extreme gust situation will be addressed. Thirdly, the aeroelastic analysis will be discussed.

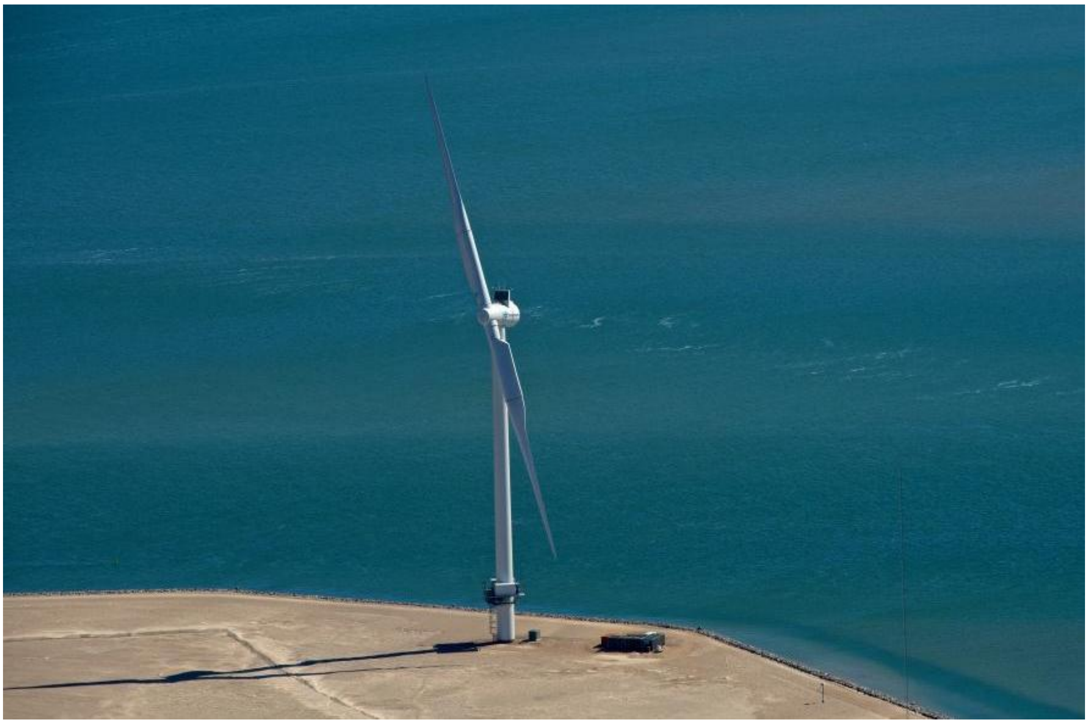


Figure 1. Envision two-bladed partial pitch turbine erected at Thyborøn in Denmark

2.1. Full-scale measurement load data selection

One of the main objectives of this paper is the load comparisons between the measured and the simulated loads during normal operations. The PP-2B turbine has been testing at Thyborøn in Denmark since 2012 September. A large amount of measurement data has been stored. From the measurement data some cases with certain criteria have been selected. For example, in order to avoid the situation where the met mast is in wake of the turbine and cases with more than 5deg yaw error. Table 1 shows statistics of the selected measurement data sets.

Table 1. Selected full-scale measurement load data set.

Case #	**Mean wind speed (m/s)**	**Mean TI (%)**	**Mean shear (α)**	**Mean yaw error (deg)**
1	5.914	5.3	0.115	4.992
2	6.992	2.1	0.174	0.962
3	7.550	3.5	0.196	1.558
4	8.555	3.0	0.219	2.478
5	9.632	2.3	0.298	2.828

2.2. Extreme wind gust

An extreme wind gust was measured at the met mast at 24 October 2013 on the test site (Thyborøn in Denmark). There was a mean wind speed at hub height of 17.8 m/s from west (see Figure 2). During a three seconds period (from 108sec. to 111sec.) the wind speed jumped from 13.6 to 23.3 m/s, the wind direction was changed from 240deg to 265deg in the rotor plane within 10sec (see Figure 2).

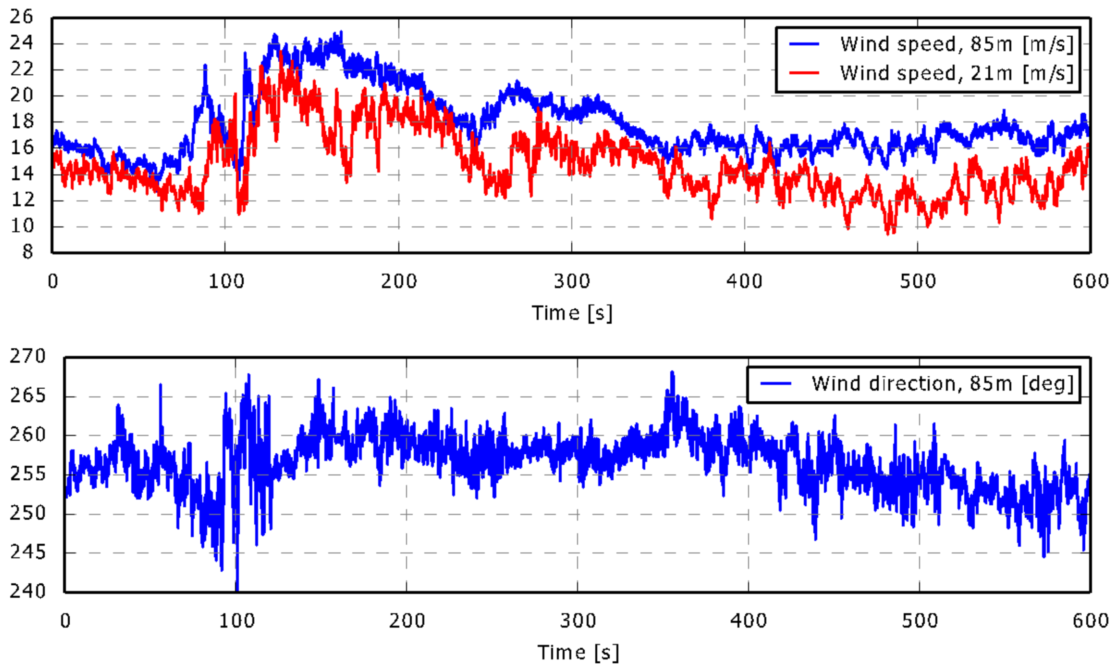


Figure 2. Wind speed and direction of measured extreme wind gust situation

In order to represent the measured wind gust for the numerical simulation a stochastic Mann turbulence model [4] is modified to match the wind speeds measured by two cup anemometers at the nearby metrological mast. The modification is performed using a method described in [1, 2]. The method finds the most probable modification of a stochastic stationary Gaussian process that meets some specified constraints, in this case the measured wind speeds. The constraint simulator implementation used here is an optimized version of an implementation made for a research project in which effects of a violent extreme negative wind shear event measured in a wind farm was analyzed [2].

In this particular study the maximum number of constraints are limited to the axial wind direction component in the two heights, 21m and 85m. This means that changes in wind direction are not modelled fully correct. It is important to realize that the simulated gust is only a perfect match where the constraint are applied. At other locations or directions, variations due to the stochastich nature occur, as it is based on a raw turbulence field with normal neutral atmospheric conditions and represent the best possible recreation under the given premises. Figure 3 and 4 show the comparisons of the longitudinal, called *u*-component, and lateral, called *v*-component, wind speed at 21 and 85 meters height together with the closest turbulence model values. An excellent agreement is seen in the *u*-components.

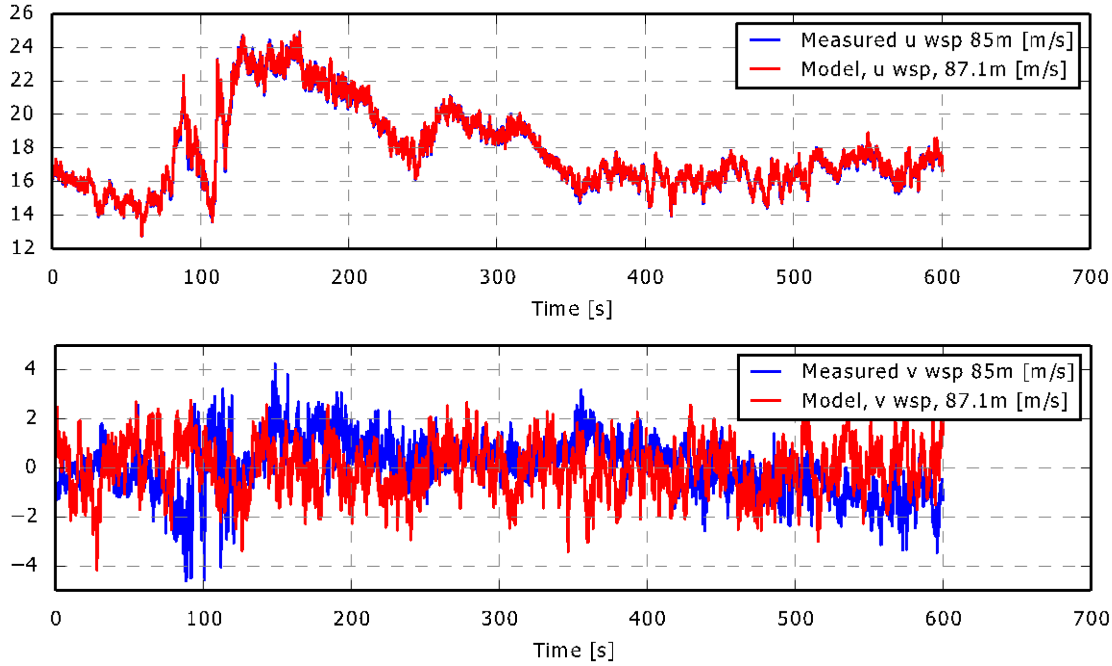


Figure 3. Measured and modelled wind speed at hub height

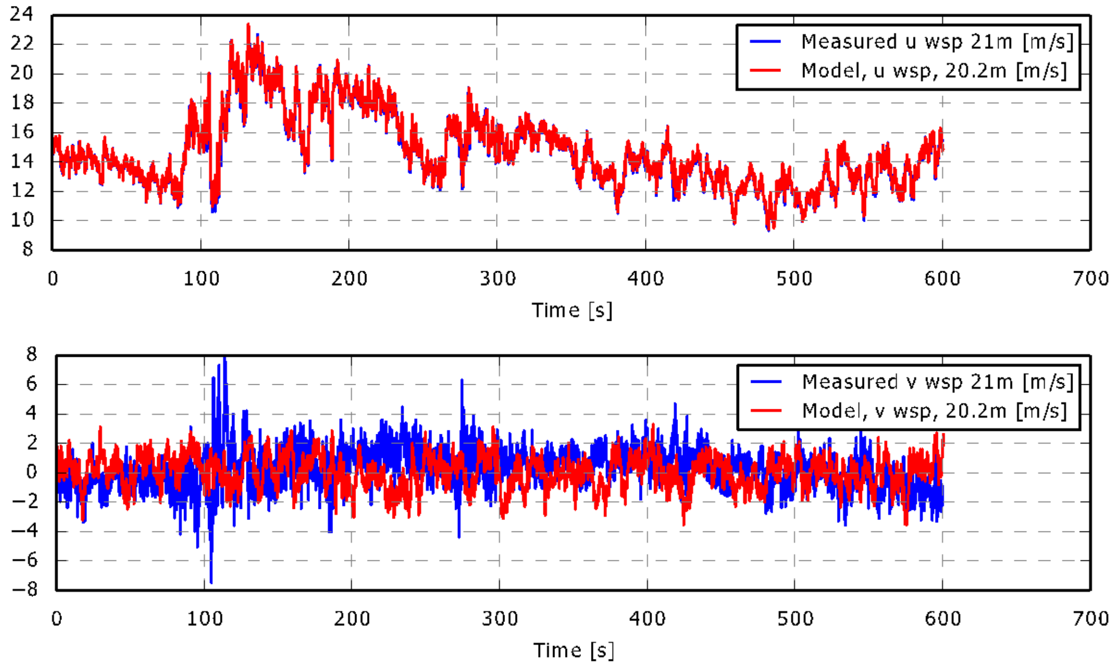


Figure 4. Measured and modelled wind speed in 21m from the ground

2.3. Aeroelastic analysis

Aeroelastic simulations have been performed with the selected measurement data set. In this study, HAWC2, which is a nonlinear aeroelastic code intended for computing wind turbine response in time domain, is used for the aeroelastic simulation [5-7]. Six different turbulence seeds are considered for each load case. Statistic results, min-mean-max values, are compared for the selected normal operation cases. Flapwise and edgewise blade bending moments and tower top bending moments are compared. In addition the generator behavior is compared for the extreme wind gust case as the extreme gust normally introduces a grid fault due to rapidly increasing rotor speed which results in an emergency shut-down situation. Figure 5 shows the sketch of sensor positions on the blade. Among 6 sensors Pos1 and Pos4 are used in this study.

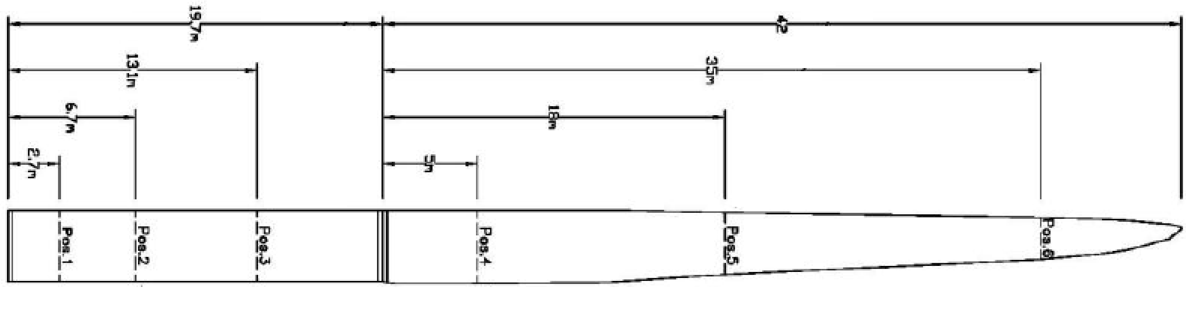


Figure 5. Sensor positions on the blade

3. Results

In this section obtained results are discussed. First of all, statistic load comparisons are addressed. Secondly, the extreme gust response is also presented.

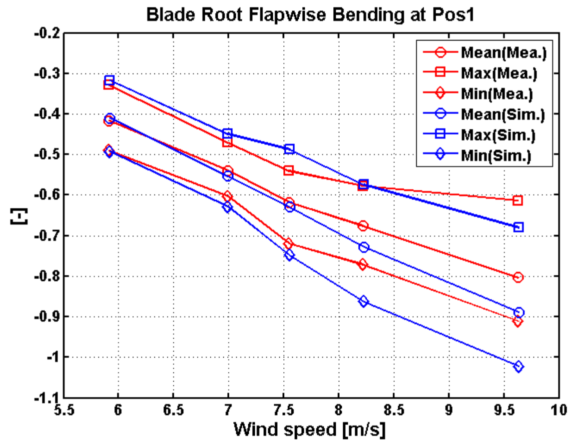
3.1. Statistic load comparisons

Blade root (both for inner and outer part of the blade, Pos1 and Pos4) flapwise and edgewise bending moments and tower top bending moments are compared. All values are normalized with the minimum flapwise bending moment at 9.632m/s (see Figure 6(a)). From Figure 6 it is clearly seen that the mean loading values are matched quite well for both the blade and the tower bending moments. However the maximum and minimum tower top bending moment at 5.914 m/s looks quite different. These discrepancies might originate from using different controllers for the simulation and the full-scale measurements. Nevertheless, in general, the statistic load comparisons between the measurement and the simulation show quite good agreement.

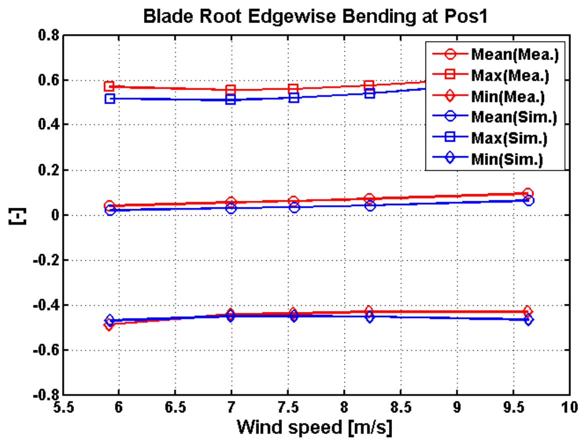
3.2. Dynamic response comparisons during the extreme wind gust

In this section the dynamic responses during the extreme wind gust are compared. Especially, the time window from 100 sec. to 120sec. is focused. It is because the interested time period is from 108sec. to 111sec. where the wind jumped approximately 10m/s. The generator rotation speed from the measurement and the simulation are compared in Figure 7. Normally the extreme gust event accelerates the rotor rapidly which makes the controller to stop the turbine to prevent over speed, however it is very clearly seen from Figure 7 that the rotor speed is not dramatically increased while the extreme gust occurs. It is also seen that the numerical model predicts the phenomenon very well. The reason for the fine behaviour of the turbine can to some degree be explained by the large rotor inertia, caused by the blade pitch bearings placed 20m from the blade root.

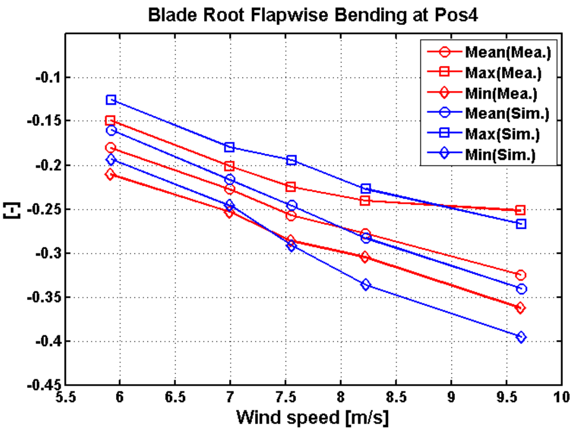
The measured and simulated blade root flapwise and edgewise bending moments at Pos1 are also compared in Figure 8 and 9. Both measurements and simulations show that the blade does not respond to the gust immediately due to the large rotor inertia. The HAWC2 simulation predicts the dynamic behaviours very well compared to the measurement.



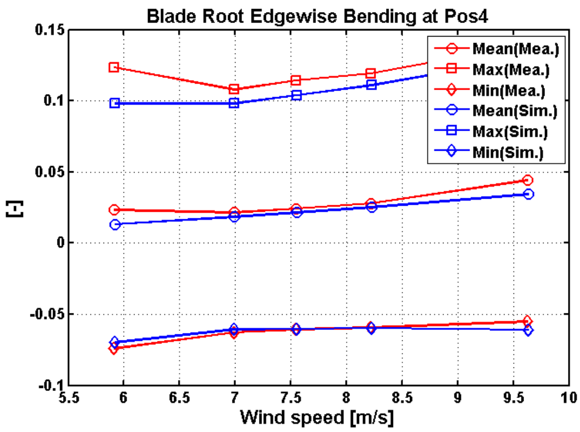
(a) blade root flapwise bending moment at Pos1



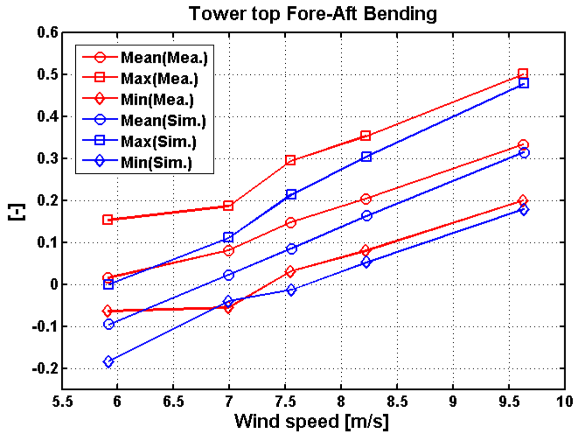
(b) blade root edgewise bending moment at Pos1



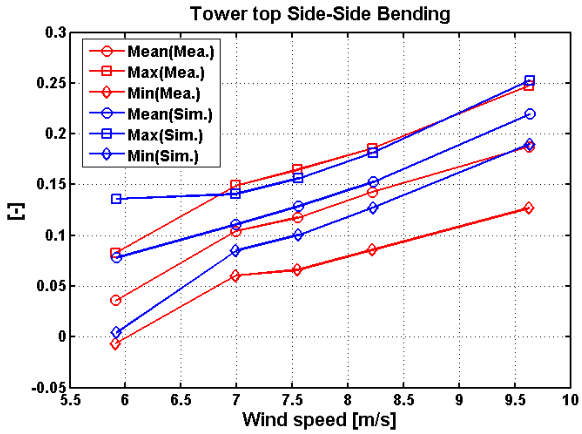
(c) blade root flapwise bending moment at Pos4



(d) blade root edgewise bending moment at Pos4

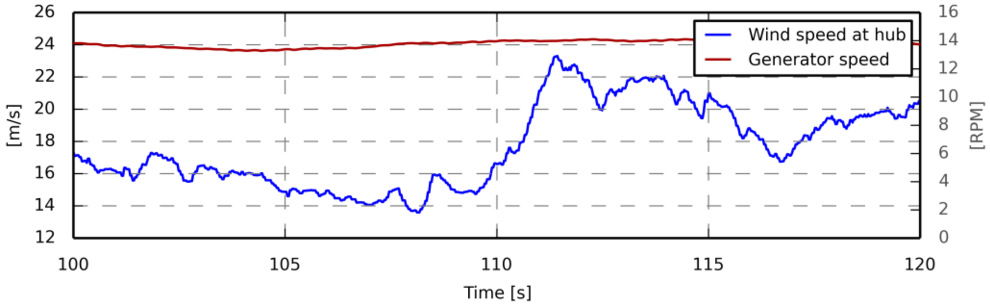


(e) tower top fore-aft bending moment

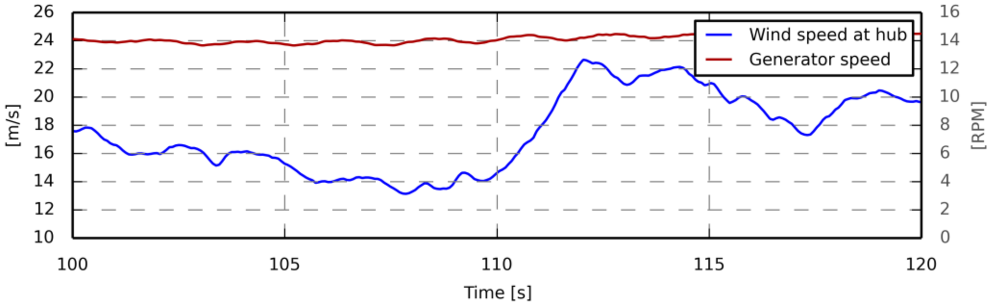


(f) tower top side-side bending moment

Figure 6. Statistic loads comparisons between measurement and simulation: in general the statistic load comparisons show quite good agreement.

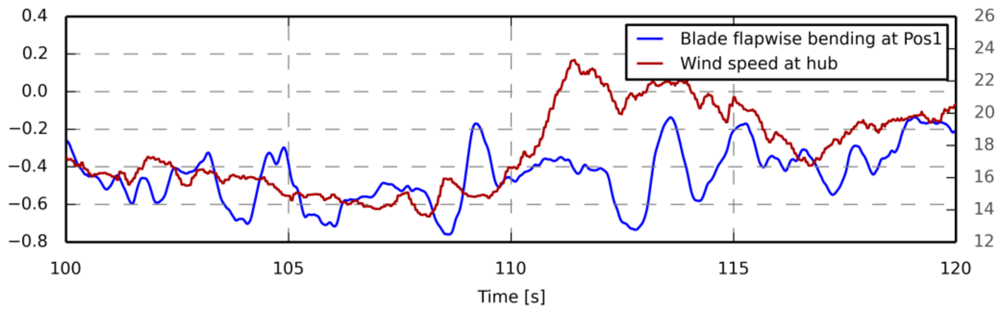


(a) Generator speed changes while wind speed changing - Measurement

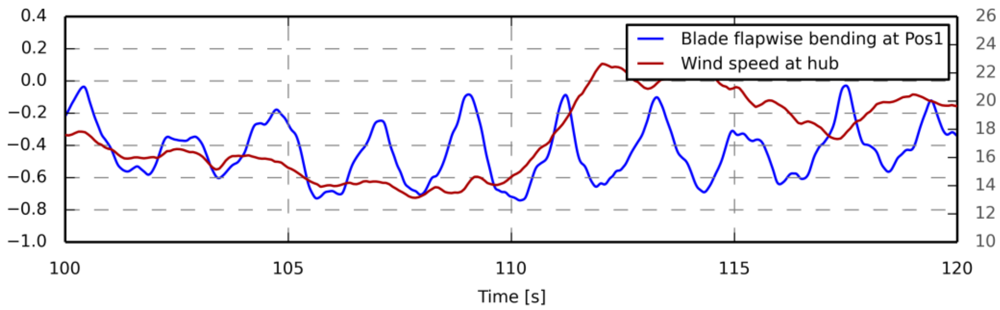


(b) Generator speed changes while wind speed changing - Simulation

Figure 7. Generator speed comparisons between the measurement and the simulation: both results show that generator speed is not dramatically increased while the wind speed changes from 13 to 23m/s.

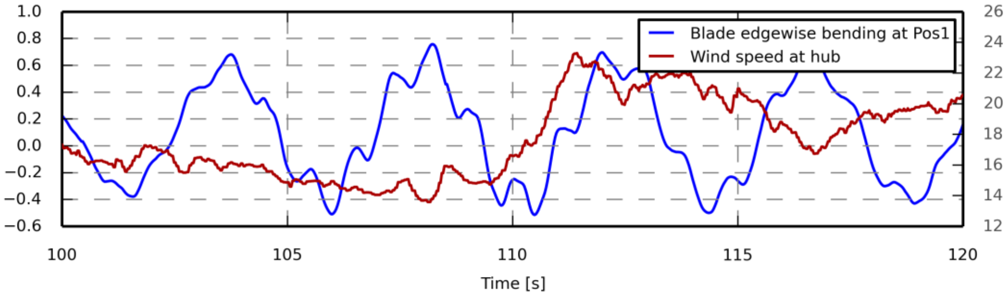


(a) Blade flapwise bending moment at Pos1 – Measurement: bending moment is normalized with the minimum flapwise bending moment at 9.632m/s (see Figure 6(a))

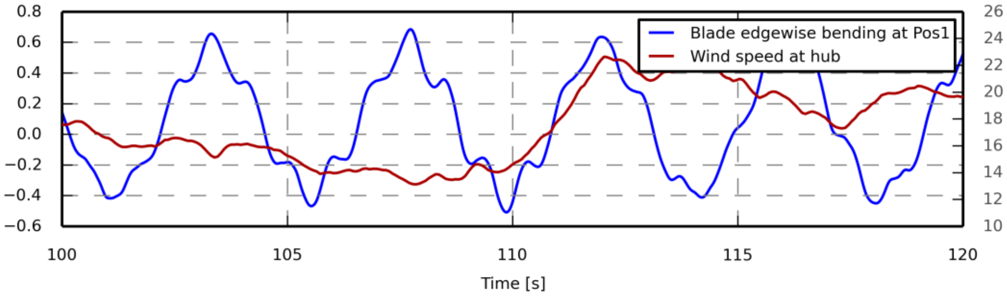


(b) Blade flapwise bending moment at Pos1 - Simulation: bending moment is normalized with the minimum flapwise bending moment at 9.632m/s (see Figure 6(a))

Figure 8. Blade root flapwise bending moment comparisons between the measurement and the simulation: both results show that blade does not immediately respond to the gust.



(a) Blade edgewise bending moment at Pos1 - Simulation: bending moment is normalized with the minimum flapwise bending moment at 9.632m/s (see Figure 6(a))



(b) Blade edgewise bending moment at Pos1 - Simulation: bending moment is normalized with the minimum flapwise bending moment at 9.632m/s (see Figure 6(a))

Figure 9. Blade root edgewise bending moment comparisons between the measurement and the simulation: both results show that blade does not immediately respond to the gust.

4. Conclusions

In this paper numerical simulation results of the two-bladed partial pitch turbine are compared with full-scale measurement data during normal operations and an extreme wind gust case. Since the Envision two-bladed partial pitch turbine was erected and tested a huge amount of measurement data has been stored. In order to select good quality measurement data, selection criteria are defined such as the wind direction, the yaw error, generator speed etc. Based on these criteria, five measurement data sets were selected. From the selected measurement data mean wind speeds, mean yaw errors, mean turbulence intensities, and mean wind shear values are extracted and used for the aeroelastic simulations where HAWC2, a nonlinear aeroelastic code, is used. Six turbulence seeds are considered for each wind speed. For the normal operation case statistic loads (Max-Mean-Min) are compared. Especially blade flapwise and edgewise bending moments and tower top bending moments are compared. A very fine agreement is seen between simulated and measured loads. An extreme wind gust case was measured at Thyborøn where the wind speed jumped from 13.6 to 23.3 m/s during three seconds. In order to reproduce the measured gust wind for the numerical simulation a stochastic Mann turbulence wind field was modified by constraint simulation to match the wind speeds measured by two cup anemometers at 21m and 85m from the ground. From the measured and the simulated response comparisons, it was found that the rotor speed and blade loads do not react quickly to the wind gust. One explanation of this is the enlarged rotor inertia caused by the blade pitch bearings placed 20m from the blade root. The numerical model seem to predict a similar response as measured also during this extreme gust.

5. Future works

In this paper only a few wind speed cases are compared. Therefore more wind speed cases will be compared. Power output will be compared as well. For the numerical simulation a different controller has been used. It might introduce load discrepancy (especially tower loading at low wind speed). Therefore the same controller will be used. In the current study the wind direction change for the numerical extreme wind gust model was not taken into account. It will be implemented in the gust model.

6. References

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Acknowledgments

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