

Assessment of synthetic winds through spectral modeling and validation using FAST

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Assessment of synthetic winds through spectral modeling and validation using FAST

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Abstract. In this paper, we analyse the simulated and measured wind data with respect to their spectral characteristics and their effect on wind turbine loads. The synthetic data is generated from a stochastic full-field turbulent wind simulator - TurbSim for neutral stability conditions. We first investigate a model for velocity spectra and, a coherence model, by comparing the model results with the measurements. In the second part we analyse the synthetic data via spectra and coherence for two cases; without and with adding coherent events. Finally, we compare wind turbine loads calculated by using FAST simulation of 5 MW reference wind turbine on the basis of simulated and measured data for the given mean wind speed.

1. Introduction

In order to have proper design and life assessment of wind turbine, it is important to have accurate prediction of wind loads. As for the precise structural modeling of the turbine a full 3-D representation of the incoming wind is needed. For this purpose tools for the synthesis of the respective data sets are based on physical understanding of the structure of the incoming wind flow [1, 2] are applied. These tools have to demonstrate that they represent the flow structure observed in the atmospheric boundary layer (ABL) and in application result in a realistic dynamic response of the wind turbines. Here the tool TurbSim [3] is subject to a respective analysis.

The TurbSim offers synthetic time series via IEC defined spectral models [4]. It can be run in a basic mode using basic Fourier synthesis based on the information of the frequency and coherence spectra and a mode respecting the intermittent characteristics of the wind flow by superimposing coherent events. In the following, two schemes

- Case 1: without adding coherent events to time-series obtained from TurbSim
- Case 2: with coherent events added to the time-series,

are used for generating wind field data sets which are subsequently passed to a dynamic wind turbine model.

The resulting data sets are first analyzed for their spectral characteristics and in addition - for their increment statistics (c.f. [5]) giving an indication of non-Gaussian characteristics of the sets. These data are compared to the respective characteristics of empirical data as offered by the server of the National Renewable Energy Laboratory (NREL) Wind turbine test center. Data used refer to tower based measurements by sonic anemometers at 100 m height above ground.



The aeroelastic computer-aided engineering tool FAST [6] for horizontal axis wind turbines is then applied for simulating the coupled dynamic response of a wind turbine. In order to distinguish the effect of coherence, we use the NREL's National Wind Technology Center Model (NWTCCUP) along with test function "KHTTEST" which superimposes one intense coherent event in the middle of the output time series [4].

The analyses are performed with the objective to assess whether superimposition of coherence events can sufficiently capture the spectral characteristics of real wind conditions. This is further evaluated based on their effect on wind turbine loads.

The basic definitions, notation, and description of the spectral and the coherence model are provided in Section 2, along with spectral analysis of measured and synthetic data. The effects from the two cases given above on wind turbine loads are shown in Section 3, along with loads calculated from measured time-series. Finally we conclude our analysis in Section 4 with discussion.

2. Spectral analysis

2.1. Model

The NWTCCUP model spectra are based on the smooth-terrain model (SMOOTH) developed by [7] and [8], and are given, for diabatic ABL's as

$$\frac{f S_i^M(f)}{u_*^2} = \frac{C_{1,i} R (\phi_\epsilon / \phi_m)^{2/3}}{1 + C_{2,i} R^{5/3}}, \quad (1)$$

where for i th velocity component, f is the frequency, u_* is the friction velocity, the ratio $R = fz/(U\phi_m)$, ϕ_ϵ and ϕ_m are the dimensionless dissipation rate and velocity gradient, respectively, and U is the mean wind speed at height z . The constants C_1 and C_2 are the scaling parameters for each component and are reported in [4].

TurbSim implements the coherence function along with the NWTCCUP spectral model, and is described as

$$\text{Coh}_i(f, r) = \exp \left(-a_i \left(\frac{r}{z_m} \right)^e \sqrt{\left(\frac{fr}{U_m} \right)^2 + (b_i r)^2} \right), \quad (2)$$

where r is the separation distance between the points on the grid, e is the coherence exponent input parameter, z_m and U_m are the mean height and mean wind speed between the two points, respectively. The variables a_i and b_i represent the decrement and offset, respectively for i th velocity component.

Letting ϕ_ϵ and ϕ_m equal to one in neutral ABL limit, the model velocity spectra normalized by u_* for the mean wind speed $U = 14.8$ m/s and $z = 100$ m, and the model coherence are shown in figure 1(a) and 1(b), respectively. The coherences are shown for $r = 50$ m, $z_m = 75$ m, $U_m = 14$ m/s, and $e = 0$. For variables a and b , we take values referring to figures (13-15) in [4], and the approximated values are $(a_u, a_v, a_w) \approx (12, 8, 5)$ and $(b_u, b_v, b_w) \approx (0.0002, 0.0005, 0.002)$.

2.2. Observations

For the spectral analysis and load calculations, we consider the measurements from sonic anemometers measuring temperature and wind speeds at 20 Hz in three dimensions on a NREL's met-mast located in southwest corner of the NWTC near Boulder, Colorado (<http://wind.nrel.gov/MetData/135mData/index.html>). The data is selected for the mean wind speed bin of 14 – 15 m/s measured at 88 m height by a cup anemometer. To avoid the wake effects on turbulence from the wind turbines, and the met-mast itself, wind are selected for the directions 250° – 310°, also measured at 88 m by a wind-vane. The NWTC is situated

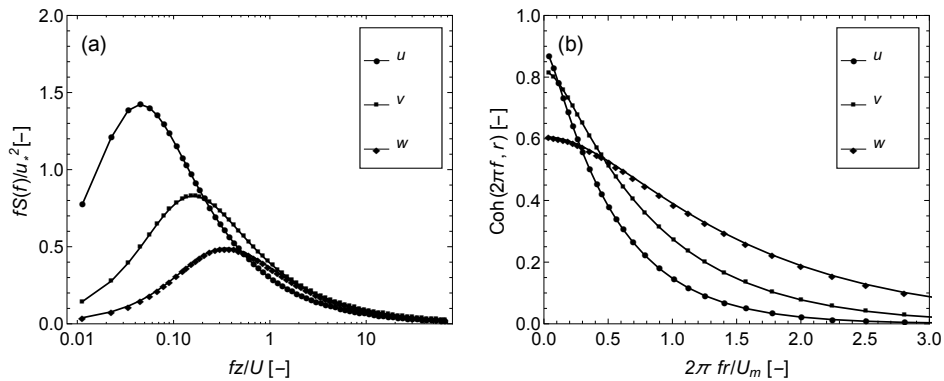


Figure 1: The model; (a) normalized velocity spectra as given in (1), for $z = 100$ m and $U = 14.8$ m/s, and (b) coherence given by (2), for the mean wind speed $U_m = 14$ m/s between two points $r = 50$ m apart.

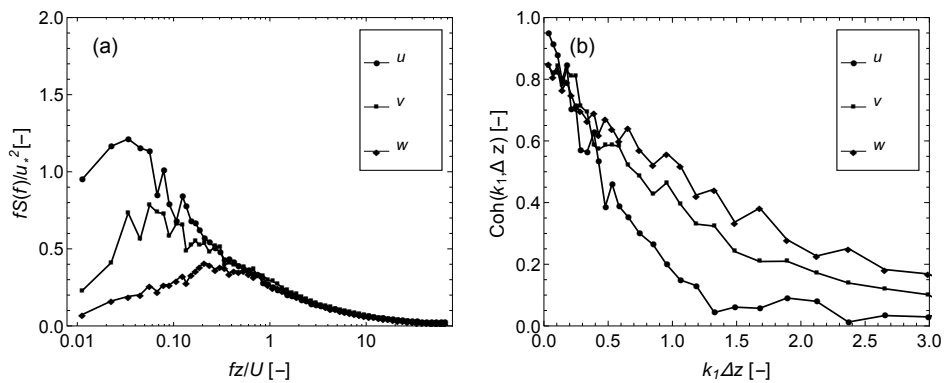


Figure 2: The observed; (a) velocity spectra at $z = 100$ m, $U \approx 14.8$ m/s, and (b) coherence between heights 50 and 100 m, and the mean wind speed ≈ 14 m/s between the two heights.

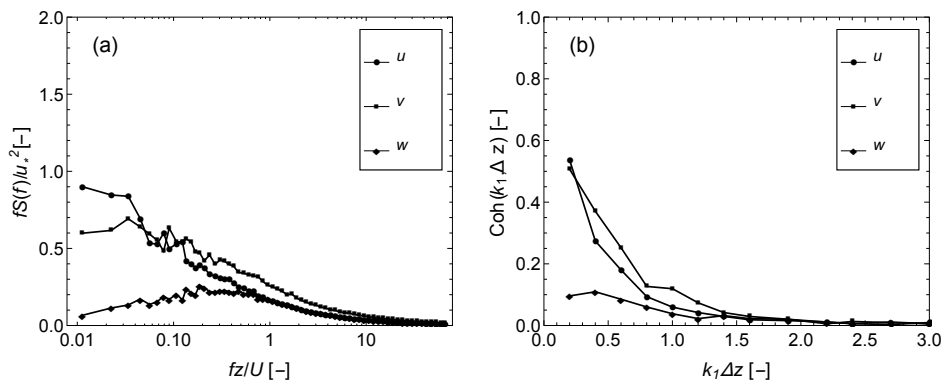


Figure 3: For Case 1, from synthetic data: (a) velocity spectra for $z = 100$ m, $U = 14.8$ m/s, and (b) coherence for $\Delta z = 50$ m between the two heights.

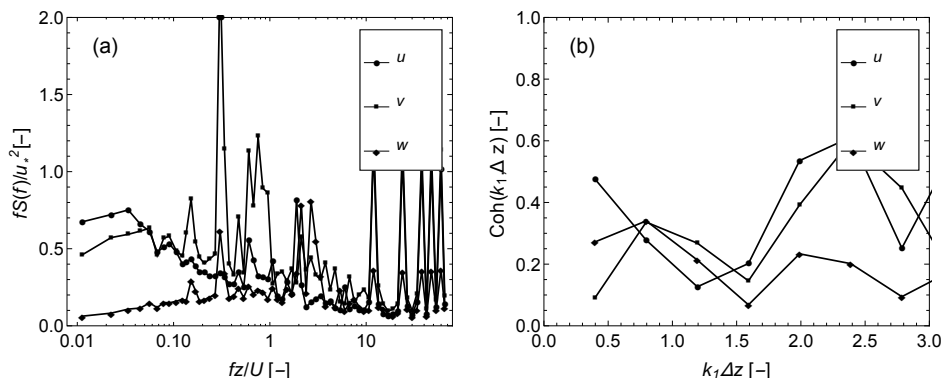


Figure 4: For Case 2, from synthetic data: (a) velocity spectra for $z = 100$ m, $U = 14.8$ m/s, and (b) coherence for $\Delta z = 50$ m between the two heights.

about 5 km to the east of the Colorado Front Range, from which the wind inflow is influenced for the sector $250^\circ - 310^\circ$.

The sonic anemometers are installed at the heights of 15, 30, 50, 76, 100 and 131 m. We analyse three years of data from 2012 to 2014. More details about the NWTC turbine inflow tower data, location, and instrumentation can be found in [9].

We estimate velocity cross-spectra between two heights, as well as the power-spectra from 10-minute time series by using basic definitions that can be found in e.g., [1]. The spatial coherences ([4]) between two points are estimated from the cross-spectra. The calculations are carried out for neutrally stratified ABL for Obukhov length ([10]) $|L_o| \geq 500$ according to [11].

The velocity spectra from the observations at $z = 100$ m and for the mean wind speed $U \approx 14.8$ m/s, and the observed coherences between heights 50 and 100 m, are shown in figure 2(a) and 2(b), respectively. One hundred and fifteen number of 10-minute time-series are used to calculate the velocity spectra and are normalized with the friction velocity $u_* \approx 0.9$ m/s at 15 m.

2.3. Synthetic data

2.3.1. Spectra and coherences We generate synthetic data using TurbSim for the given conditions; i.e., $z = 100$ m, $U = 14.8$ m/s, $u_* = 0.9$, and the gradient Richardson number $Ri = 0$. The velocity spectra and the coherence for a 50 m vertical separation for Case 1, are given in figure 3(a) and 3(b), respectively. The spectra and cross-spectra are averaged over one hundred and fifteen random seeds generating corresponding 10-minute time-series.

The velocity spectra and coherences for Case 2 are shown in figure 4 for the same wind conditions given above for Case 1, except that the coherent events added to the synthetic data in Case 2. It is noted that the spectra and coherences from Case 1 are underestimated, while the inertial sub-range within the spectra are not well settled in Case 2, and also, the coherence from Case 2 are increased at smaller scales (or higher frequencies).

2.3.2. Velocity increments As mentioned above, it is expected that the increments from the measured data show non-Gaussian characteristics (see e.g. [12]), a property that is as well gained from analyzing the series generated by Large Eddy Simulation (LES) schemes (see e.g. [5]). The templates for the coherent structures used here by the “KHTEST” scheme stem from that origin. Here we inspect the similarity of the increment statistics of the empirical and synthetic sets generated by applying the default setting of the TurbSim “KHTEST” scheme.

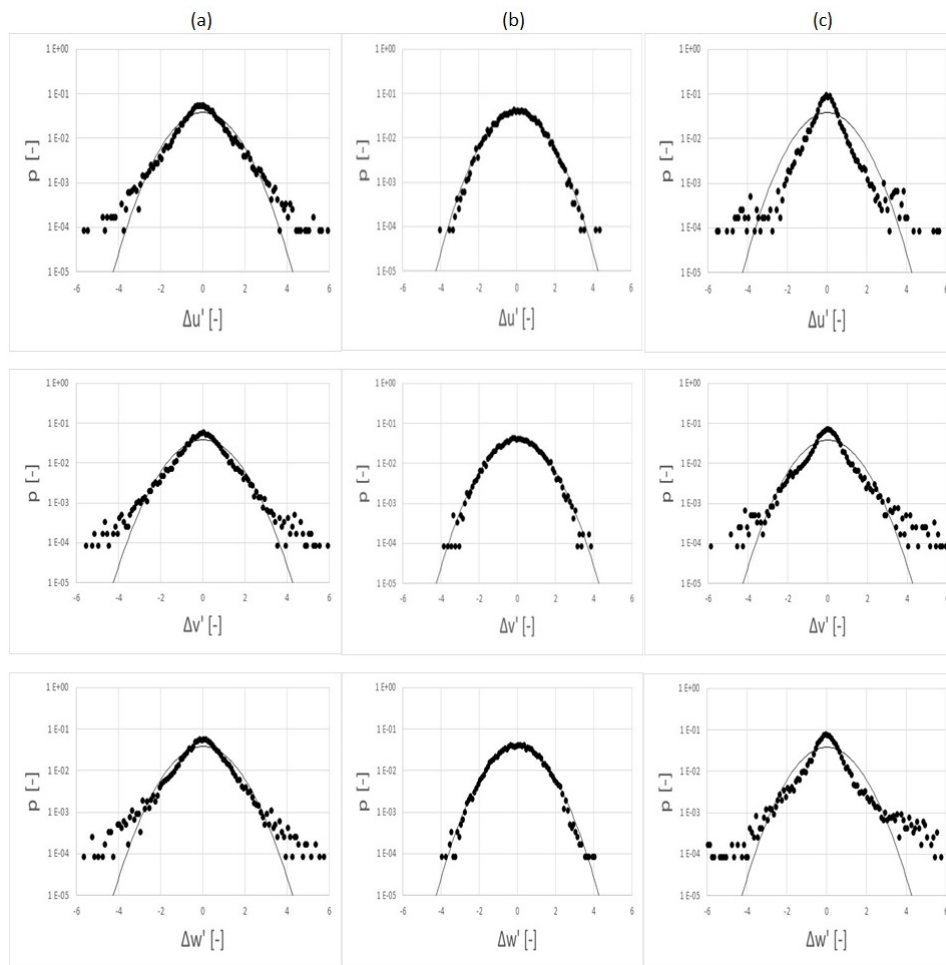


Figure 5: Probability distributions of the increments Δ , normalized by standard deviation of increments in u (first row), v (second row), and w (third row), for (a) 10-minute measured time-series, (b) Case 1: synthetic data from TurbSim without coherent events added, and (c) Case 2: synthetic time-series with coherent event added.

Figures in 5(a) give the probability distributions (PDF) of the increments Δ , normalized by standard deviation of increments, on the 20 Hz scale for the three velocity components. The deviations from a Gaussian distribution are obvious for all components. To be considered as equivalent the synthetic data have to show the same characteristics. Obviously for data sets generated by the basic TurbSim procedure without inclusion of coherent events there is a negative result (see figure 5(b)).

The inclusion of the coherent events in the generation procedure results in the distributions of increments as given in figure 5(c). The PDFs prove the non-Gaussian characteristics of this synthetic set. However, it is obvious that, for a proper reflection of the empirical characteristics parameters that determine the negotiation of the coherent events have to be tuned. Thus for a general applicable synthetization scheme both, modeling of the PDFs of the increment in dependence of the flow situation (mean wind speed, turbulence intensity, thermal stratification, etc.) and the proper settings of the parameters of the scheme for the inclusion of coherent events to approach these PDFs have to be identified.

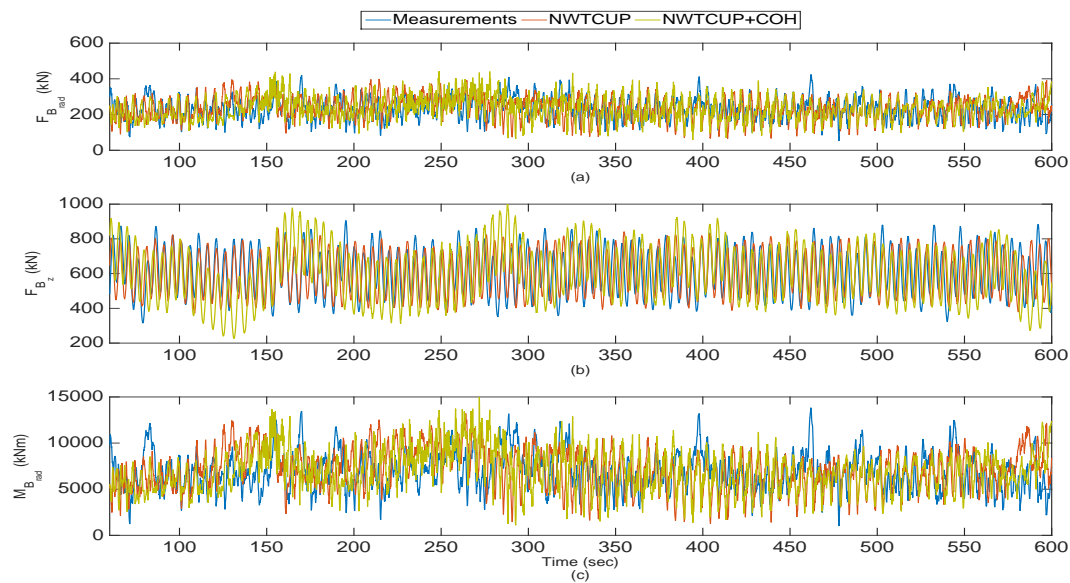


Figure 6: Comparison of blade loads.

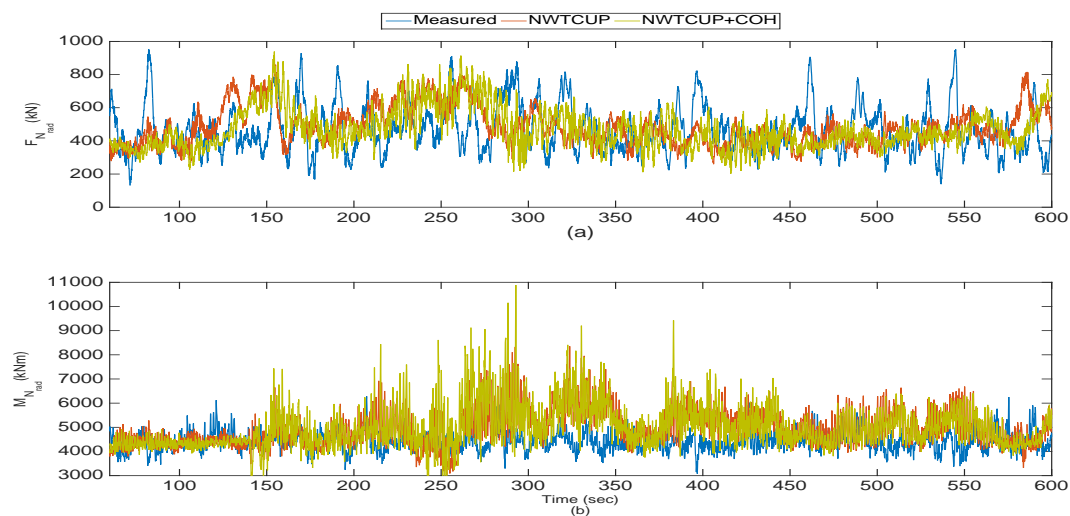


Figure 7: Comparison of nacelle loads.

3. Wind turbine load analysis

The loads on wind turbine due to various wind conditions are studied based on simulations using FAST analysis tool developed by National Renewable Energy Laboratory. FAST is a coupled simulation platform including wind in-flow, aerodynamics, structural dynamics and controls for wind turbines. The 5MW reference wind turbine is simulated in onshore configuration using the synthetic data generated from TurbSim as well as the measured data. The turbine is controlled by ‘GH Bladed style’ dll controller that controls the generator, collective pitch and yaw systems [13].

In case of synthetic data, the turbine is firstly simulated using the NWTcup model as

Table 1: Ratio of maximum loads seen at blade-root and nacelle bearing Case (1): NWTCUP model, Case (2): NWTCUP model with superimposed coherence and Case (3): measurement data.

Ratio	$RootF_{x_{c1}}$	$RootF_{y_{c1}}$	$RootF_{z_{c1}}$	$RootM_{x_{c1}}$	$RootM_{y_{c1}}$	$RootM_{z_{c1}}$
(3)/(1)	0.9921	1.0296	1.023	1.0154	0.9549	1.2165
(3)/(2)	0.9824	0.8308	0.7572	0.8213	0.9687	0.7870
	$YawBrF_{x_p}$	$YawBrF_{y_p}$	$YawBrF_{z_p}$	$YawBrM_{x_p}$	$YawBrM_{y_p}$	$YawBrM_{z_p}$
(3)/(1)	0.8578	1.3627	1.0209	1.0143	1.1951	1.3413
(3)/(2)	0.9986	0.7701	1.030	0.9905	0.9953	0.8696

Table 2: Comparison of damage-equivalent loads Case (1): NWTCUP, Case (2): NWTCUP with superimposed coherence and Case (3): measured data.

Case	$RootF_{x_{c1}}$ (kN)	$RootF_{y_{c1}}$ (kN)	$RootF_{z_{c1}}$ (kN)	$RootM_{x_{c1}}$ (kNm)	$RootM_{y_{c1}}$ (kNm)	$RootM_{z_{c1}}$ (kNm)
(1)	$2.385e + 02$	$3.284e + 02$	$5.562e + 02$	$7.060e + 03$	$9.061e + 03$	$1.194e + 02$
(2)	$2.383e + 02$	$3.432e + 02$	$9.559e + 02$	$7.634e + 03$	$8.857e + 03$	$1.597e + 02$
(3)	$2.530e + 02$	$3.273e + 02$	$6.052e + 02$	$6.992e + 03$	$9.445e + 03$	$1.335e + 02$
	$YawBrF_{x_p}$ (kN)	$YawBrF_{y_p}$ (kN)	$YawBrF_{z_p}$ (kN)	$YawBrM_{x_p}$ (kNm)	$YawBrM_{y_p}$ (kNm)	$YawBrM_{z_p}$ (kNm)
(1)	$2.995e + 02$	$5.614e + 01$	$1.503e + 02$	$1.328e + 03$	$3.625e + 03$	$2.833e + 03$
(2)	$3.096e + 02$	$1.204e + 02$	$2.301e + 02$	$1.641e + 03$	$4.380e + 03$	$3.718e + 03$
(3)	$3.211e + 02$	$8.201e + 01$	$1.713e + 02$	$1.394e + 03$	$3.158e + 03$	$2.986e + 03$

described earlier, without superimposing the coherence events. Further, the coherent events are superimposed using the “KHTEST” option and the magnitude of scales are tuned. In case of the measured data, TurbSim Alpha [14] is used to generate full-field wind files. The mast data at heights of 15, 30, 50, 76, 100 and 131 m is supplied to the software. TurbSim Alpha calculates full-field wind data based on the specified turbulence spectra and linearly interpolates the velocity and direction profiles to match the specified time series.

The effect of coherence on loads in measured data and simulated data are compared in terms of blade root loads and the nacelle bearing loads. The blade root loads corresponding to blade 1 are the radial and axial forces [$RootF_{x_{c1}}$, $RootF_{y_{c1}}$, $RootF_{z_{c1}}$] and corresponding moments [$RootM_{x_{c1}}$, $RootM_{y_{c1}}$, $RootM_{z_{c1}}$]. Similarly, the nacelle radial and axial forces [$YawBrF_{x_p}$, $YawBrF_{y_p}$, $YawBrF_{z_p}$] and corresponding moments are [$YawBrM_{x_p}$, $YawBrM_{y_p}$, $YawBrM_{z_p}$]. In each case, namely, the NWTCUP without coherence events, NWTCUP with coherence events, and the measured data, 115 samples of 10-minute duration are collected and simulated with the wind turbine. For one such simulation, the blade root loads are showcased in figure 6 and the nacelle bearing loads are shown in figure 7.

The results from the wind turbine are further post-processed using NREL’s MLife [15] in order to determine aggregate statistics and damage equivalent loads (DELs) as described in [16]. The damage equivalent loads are a measure of equivalent fatigue damage caused by the loads taking into account the material properties, namely the S-N curves (Wöhler exponents).

The ultimate loads are determined using MExtremes [17]. As this is a large set of data, only specific information relevant to the analysis is presented here.

Across the data sets, the worst case (maximum loads) are compared for the synthetic data against the measured data. These ratios for blade root and nacelle forces and moments are calculated from the aggregate statistics of time-series data of all the simulations. In these calculations however, the first minute of simulation is excluded in order to account for the initial conditions. The ratios are presented in Table 1. It can be noted that the NWTcup with superimposed coherence events produces load effects more conservatively. It is to be noted that the scaling parameters for the coherence events need to be tuned for the given measurement data in order to obtain a realistic representation.

The damage-equivalent loads for the three cases are showcased in Table 2. These are the aggregate DEL's over 115 test cases, that is, 50,000 equivalent cycles. The S-N slope 10 is chosen for the composite blade and 3 for steel nacelle. Similar to the aggregate load statistics, the NWTcup with superimposed coherence events results in a conservative DEL's compared to its counterpart. Besides, it is evident that finer tuning of the coherent event scales are necessary for a closer fit.

4. Discussion and conclusion

It is seen that the spectral model given by (1) has u -spectrum slightly higher than the observed (figures 1(a) and 2(a)), whereas the coherence model in (2) having the velocity coherences slightly underestimated. The model show the w -coherence smaller at low frequencies and larger at higher frequencies, which can also be seen in the observed coherence (figures 1(b) and 2(b)).

Both the velocity spectra and coherences are observed to be increased (at higher frequencies) due to the addition of coherent events in the synthetic data in Case 2, whereas those are underestimated in Case 1. Although the basic models that are used in simulations show reasonable agreements, the results from the synthetic data depart from the observations. The spectra and coherence results from Case 2 show that the coherence events which are added to the time-series need to be scale-dependent.

From the probability distributions of the increments, qualitatively the coherent events lead to deviations from Gaussian characteristics, but not directly matching the deviations extracted from the measured sets (and consequently will result in different load characteristics when applied).

We analysed the wind turbine loads via FAST simulations for two cases, with and without coherent events added to the synthetic data, in comparison to the loads calculations based on the measured data. The synthetic data without superimposed coherent events can be seen to underestimate the loads as opposed to the case with superimposed spectral events. However, the scaling parameters for the coherent events need to be tuned for the given measurement data. Similar effect was also noticed in the case of calculation of damage equivalent loads.

Finally, topics for further research we conclude are to be identified here:

- For general applicability, parameters of models used (e.g., [18]) for the characterizations of the distributions of the increment have to be linked to basic parameters of the wind field (e.g. mean wind speed, turbulence intensity, thermal stability, etc.)
- The procedure for the implementation of the coherent events must be extended to be tunable to generate the desired frequency dependent statistical characteristics ([12]), as well as wind turbine loads
- The study can be extended for non-neutral ABL's indicating possible optimized scales to which the coherent events are added to the synthetic time-series in order the maximum loads and moments to be more close to the reality, along with studying a site-specific occurrences of different atmospheric stabilities.

- Measures for testing of the equivalence of statistics of synthetic to measured winds beyond spectral power density and coherences are still incomplete.

Acknowledgements

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