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A comparison of fatigue loads of wind turbine resulting from a non-Gaussian turbulence model vs. standard ones

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Abstract. This project funded by the federal ministry of education and research from the research group ‘Wind turbulence and its significance in the use of wind energy’ handles a comparison between the load ranges for horizontal axis wind turbines resulting from different turbulence models, i.e. between the usual models as defined in the standards and a new model designed by Friedrich and Kleinhans. This should enable an evaluation of the relevance of this new model for wind modelling for wind turbines and if so, provide the community with new tools in wind simulation. Indeed, spectral models do not well reproduce extreme wind increments as met in gusts. Those models simulate using purely Gaussian statistics. However, measurements show that those increments do not follow normal statistics as shown in figure 2. The new model developed aims at correcting this problem. The turbulence models used are the Kaimal, von Karman and Mann models as defined in the IEC guidelines and the Friedrich-Kleinhans model, based on stochastic processes called Continuous Time Random Walks. The comparison is based on load ranges resulting from an RFC analysis of 100 time series obtained for 100 different seed numbers. Five wind speeds are investigated. The aeroelastic code used is FLEX5. The main conclusion that can be drawn from this study is that the non-Gaussian Friedrich-Kleinhans model produces loads that are significantly different from the loads obtained with the Kaimal model. That proves that the form of the tails of the increment distribution has a major influence on the loads of the wind turbine and should be considered when making fatigue calculations.

1. Introduction

1.1 Increment distribution

In this paper, a comparison is undertaken between the load ranges resulting from different turbulence models, i.e. between the usual models as defined in the standards and a new model designed by Friedrich and Kleinhans. This should enable an evaluation of the relevance of this new model for wind modelling for wind turbines and if so, provide the community with new tools in wind simulation.

Indeed, spectral models do not well reproduce extreme wind increments as met in gusts. Those models simulate using purely Gaussian statistics, as can be seen in figure 1. However, measurements show that those increments do not follow normal statistics as shown in figure 2. The new model developed aims at correcting this problem. Atmospheric wind measurements show a high variability in space and time and, therefore, cannot be modelled by Markovian stochastic processes. From a mathematical point of view, Continuous Time Random Walks processes represent the minimal model to produce non-Markovian data sequences by means of stochastic processes [12]. The wind speed data for figure 2 was surveyed by a cup anemometer at 81 m above ground at a sampling frequency of 1 Hz. From
this data pool, data sets with a 10-min mean wind speed of 10±0.25 m/s were selected and analyzed with respect to the increment statistics.

![Figure 1](image1.png)  
**Figure 1.** Spectral surrogates generated by TurbSim: Distribution of the increments for time lags 1s, 5s, 10s, 30s, and 60s respectively (bottom-up), normalized to $\sigma = 1$. The thin line depicts a Gaussian distribution with $\sigma = 1$. For clarity, individual distributions are shifted vertically. From [5].

![Figure 2](image2.png)  
**Figure 2.** Analysis of atmospheric measurements [5]: Distribution of the increments for time lags 1s, 5s, 10s, 30s, and 60s respectively (bottom-up), normalized to $\sigma = 1$. From [5]. Individual distributions are shifted vertically.

### 1.2 Contents

First, the turbulence models are presented along with the wind generation method used. A comparison between these models is shown. Then, the parameters chosen for the wind simulation are given as well as the load cases that are investigated in this paper. With these time series, the loads are calculated as explained in part 4 and the results are commented in part 5. In part 6, a conclusion is drawn. The results are shown in the appendix.

### 2. Turbulence models,

#### 2.1. Standard models: Kaimal and von Karman

The Friedrich-Kleinhans model is compared with the turbulence models taken from the IEC 61400-1 of 2004/2006 [1] and [7]. The corresponding design load case is NTM (Normal Turbulence Model) as defined in [1]. The edition of 2004 proposes the Kaimal and von Karman models, in the edition of 2006, the von Karman model has been withdrawn and replaced by the Mann model [4]. The Mann model is handled in part 2.3. All the standard models are Gaussian.

The turbulence models are defined by their power spectra $S$ and their coherences $\text{Cho}$, whose equations are given in the standards. The only parameters intervening in these equations are lengths, also precisely defined in the standards. In our case, the hub height is 100m, which means integral length scales for the Kaimal model of $L_u = 170.1m$, $L_v = 56.7m$, $L_w = 13.86m$ and $L_c = 73.5m$ (edition 2004). In the edition of 2006 of the IEC guidelines, those lengths are doubled as the parameter $\Lambda$ is 42m instead of 21m for a hub height higher than 60m. We have for the Kaimal model the following ratios between the standard deviations of the different wind components, as defined in the standards: $\sigma_2 = 0.8*\sigma_1$ and $\sigma_3 = 0.5*\sigma_1$. Being isotropic, the von Karman model has the ratios: $\sigma_1 = \sigma_2 = \sigma_3$.

Those models have been integrated in Windsim7, the wind generator of Flex5.

The spectrum and coherence have been plotted in the following figures.
2.2. Wind generation method: Sandia/Veers

The wind is generated with Windsim7 based on the Sandia-Veers Method [2]. Here, the wind components u, v, w are simulated separately, i.e. no u-w correlation is taken into account, which is physically not correct, as measurements hint at such a correlation. The wind field is first described in a spatial and spectral space to be then integrated by an FFT to get wind speeds with time dependency.

2.3. The Mann model

The main advantage of the Mann model is that it calculates a u-w correlation. The Mann model should then be a better representation of a turbulent wind.

2.3.1. Wave vector space. In opposition to the spectral Sandia/Veers method, the Mann model considers a space of wave vectors, which are a way of representing the turbulent eddies. The wave vector $\mathbf{k} = (k_1, k_2, k_3)$ is built from the components in the three spatial directions $k_1$ (longitudinal), $k_2$ (transversal) and $k_3$ (vertical). One can understand them as a measure of the size of the eddies in each direction, from the biggest eddies for the smallest $k$ to the smallest eddies for the biggest $k$. The $k_i$ are defined with $k_i = \frac{i\pi}{L_i}$ with $L_i$ the length scale which represents logically the biggest eddy in the considered direction and also the size of the simulated box one wants to simulate. We have therefore $L_i = U \cdot T$, with U the mean wind speed and T the simulation time. The simulation of the time series with the Mann model happens in this wave vector space and the wind speeds are expressed in a spatial space (x,y,z) only through the final FFT. We obtain eventually for each point of the space where we want to obtain a turbulence field, i.e. for each point of the grid, the value of the wind speed in the three directions u, v and w. The Taylor’s frozen turbulence theory authorizes such a procedure of translating a field of turbulence through the rotor plan. It is then equivalent to calculate a spatial field of turbulence with no consideration of time steps and to calculate turbulence values at the same spatial position (rotor plan) for different time steps. The first method is used here, the latter in the Sandia/Veers method. The Sandia/Veers method does a Fourier transform from frequencies to time steps, the Mann method does a Fourier transform from wave numbers to spatial steps.

2.3.2. Spectral tensor. The Mann model starts from the spectral tensor $\Phi$ calculated with the energy spectrum $E(k)$ as suggested by von Karman. The spectral tensor is a more natural and direct representation of the turbulent flow, but doesn’t contain more information than the cross-spectra. It contains all second-order statistics that are needed to generate time series. Von Karman rings the bell of isotropy and this isotropic tensor is then deformed by the vertical shear to give an anisotropic description of the turbulence in the wave vector space ($k_1$, $k_2$, $k_3$). The way the tensor is obtained is described in [3], involving a linearization of the Navier-Stokes equations and a modelling of eddy lifetimes, and the equations of the tensor components $\Phi_{ij}(k_1,k_2,k_3)$ are described in [7]. A parameter $\Gamma$ determining the anisotropy for the tensor has to be chosen and Mann proposes in [3] the value 3.9,
obtained from a fit with the Kaimal spectrum. $\Gamma$ is used to calculate $\beta$, representing the eddy lifetime. The following figures show the spectrum and the coherence for $\Gamma=3.9$, $L=29.4\text{m}$.

![Figure 5. Power spectrum $F_{11}$, $F_{22}$, $F_{33}$ on a double logarithmic scale for $\Gamma=3.9$ and $L=29.4\text{m}$.](image1)

![Figure 6. Coherence for the 3 components u, v, w for $\Gamma=3.9$ and $L=29.4\text{m}$, $D=30\text{m}$.](image2)

2.3.3. **Wind field.** The Mann model obtains from the spectral tensor a stochastic wind field. This latter can be represented in terms of a generalized stochastic Fourier-Stieltjes integral. The equations and process are to be found in [3], [8] and [9] and shall not be developed here.

2.3.4. **A few parameters.** The value of $\Gamma$ and $L$ have been taken equal to the ones proposed in the guidelines i.e. $\Gamma=3.9$ and $L=29.4\text{m}$ for a hub height of 100m. The discretisation of the space have been done with $N_1=4096$, $N_2=N_3=32$ points. The length $L_2$ and $L_3$ are taken equal to 164m for a radius of the rotor of about 42m. The time series produced are 614s long, which gives a time step of 0.15s.

2.4. **Friedrich-Kleinhans model**

A new method for the stochastic simulation of wind fields is used [5]. In contrast to the broad class of simulation algorithms in the Fourier domain [2, 3], we consider simulation in real space. While the spectral properties such as the power spectrum are more difficult to achieve in this domain, it is a more natural representation for intermittent, coherent effects including wind gusts. In [6], Friedrich showed that this type of non-Gaussian Statistics can be derived from Navier-Stokes Equations directly.

2.4.1. **Continuous Time Random Walk.** The simulation is based on the theory of "continuous time random walks" (CTRW) that forms a generalization of random walk processes [4]. A CTRW $x_s(t_i)$ is iteratively defined by

$$x_{i+1} = x_i + \eta_{i+1} \quad \text{and} \quad t_{i+1} = t_i + \tau_i \quad (1)$$

for $i \in \mathbb{N}$, $x_0 = t_0 = 0$, $\tau_i \geq 0 \forall i$. $\eta_i$ and $\tau_i$ are the step width and the waiting time, respectively, of the step $i$ and generally are random numbers. By transition of the discrete variable $i$ to a continuous intrinsic time $s$ the process becomes applicable to physical problems. In this context, the above-mentioned equations become stochastic differential equations, coupled via the intrinsic time $s$. The latter equation in this case corresponds to a mapping of the intrinsic time $s$ on the physical time $t$. Figure 7 shows a CTRW, the thin line marks a realization of the process provided by the discrete equations. The thick line forms an expansion to a continuous process that can then be adapted to special needs and in our case enables the application to turbulence generation.
2.4.2. Wind field generation. Wind field data is simulated by means of coupled stochastic Ornstein-Uhlenbeck processes. The three wind components $u$, $v$ and $w$ are simulated separately, as is the case for the Sandia-method. The wind components $u_i$, with $i = u, v, w$, follow the stochastic differential (Langevin-) equations:

\[
\frac{d}{ds} u_{\text{ref}}(s) = -\gamma_{\text{ref}} (u_{\text{ref}} - u_0) + D_{\text{ref}} \Gamma_{\text{ref}}^u(s) \quad \text{and} \quad \frac{d}{ds} u_i(s) = -\gamma (u_i - u_i^{\text{ref}}) + \sum_j D_{ij} \Gamma_{ij}^u(s)
\]

where $\Gamma_{\text{ref}}$ and $\Gamma_{ij}$ are Gaussian distributed, independent random variables. $u_0$ is the mean wind speed at hub height of the component $u$ on the whole time series. $u_{\text{ref}}$ represents the local mean wind speed at hub height and is defined by the first of the two equations. $u_{\text{ref}}$ is distributed normally around $u_0$. We have here a difference with the spectral models, which consider a constant mean wind speed, the turbulence fluctuating around this value. In the Friedrich-Kleinheins model, the local mean wind speed varies with the time. The diffusion matrix $D_{ij}$ contains the information on the correlation of two points $i$ and $j$ of the grid. The correlation has been considered as decaying exponentially with the Euclidian distance of the grid points. Finally, the constants $\alpha_i$ governs the height profile, which is logarithmic.

With these equations, the wind components are simulated for the intrinsic time $s$. The last step is to transform this intrinsic time into a physical time $t$. This is done by an independent stochastic process with the following mapping equation, by which the intermittencies are simulated.

\[
\frac{d}{ds} t(s) = \tau(s)
\]

with $\tau(s) > 0$ a stochastic variable. So far, truncated and skewed Levy distributions were applied although other classes, such as log-normal distributions, would also be feasible. An example of Levy distributions for different values of the stability parameter alpha is shown in figure 8. For an algorithm for the numerical simulation of Levy-distributed random variables, we refer to [11].

Figure 7. Schematic view of a continuous time random walk (CTRW). From [5]
2.4.3. Increment distribution. As a result, stochastic wind fields with intermittent increment distributions on a broad range of scales are obtained. Figure 9 shows the distribution of increments. The distribution is no longer Gaussian and fits the measurements much better than spectral models. Therefore, the probability of extreme wind gusts is better represented.

![Figure 8. Example of Levy distributions for different alphas](image)

2.4.4. Turbulence intensity. The ratios between the turbulence intensities of the three wind components of the Friedrich-Kleinhans wind field have been taken equal to the ones for the Kaimal model.

3. Wind generation

3.1. Physical characteristics
We consider a single turbine of class A in a neutral atmosphere at a height of 100m over a flat terrain (roughness length $z_0 = 0.01$). The characteristic lengths of the turbulence eddies are taken as defined in 2.1. The turbulence intensity $I$ is defined as in [1], depending on the mean wind speed.

3.2. Wind simulation
Time series are generated for 6 different wind speeds: 5m/s, 8m/s, 10m/s, 12m/s, 15m/s, 18m/s. For each wind speed, hundred time series are calculated for hundred different seed numbers. This ensures that the variations in the distribution of turbulence depending on the seed number are well taken into account. We have 9 radial stations and 35 azimuth stations. The time step is 0.15s for 4096 steps.

4. Load calculations

4.1. Description of the wind turbine
The loads are calculated using a model of the D8 wind turbine from DeWind. Main characteristics are a hub height of 100m, a rated wind speed of 13.5m/s, a diameter of 80m, a rated power of 2MW. It is a pitch turbine with variable rotational speed.

4.2. Calculation procedure
The calculations are carried out with FLEX5 for time series of 600s. We are considering the edgewise and flapwise moment as well as the resulting moment at the blade root and the tilt moment $M_{yt}$ at the tower top. The resulting moment is the module of the flapwise moment and the edgewise moment. The loads are first obtained as time series from FLEX5 with which we do a Rainflow Counting (RFC) analysis. The slope exponent of the materials for the RFC calculations is 12 (fibre glass) at the blade root and 4 (steel) at the tower top. $F_{ref}$ is taken 1Hz. The loads obtained are represented in cumulated repartitions. The loads are given as percentages of the mean value of the 100 load ranges or of the 100 maximal moments obtained for the Kaimal model. Therefore “higher” or “lower” means higher or lower than the loads obtained for the Kaimal model and the values given as example are related to the 100% of the Kaimal model. “Decrease” is also in comparison with the Kaimal model. In the following section, the cumulated distributions of the load ranges and of the maximal values of the moments investigated are presented for two wind speeds only for each load because of lack of space. This should be enough to show the trends with the wind speed that are announced. The graphics are shown in the appendix A. The results from the Mann-model are not presented here, as they were not available at the time of writing this paper.

5. Results

5.1. Edgewise moment at the blade root: load ranges
The values for the Friedrich-Kleinhans model are lower and decrease with the wind speed from a mean value of 93.5% for 5m/s to 80.5% for 18m/s. See figures A1 and A2.

5.2. Flapwise moment at the blade root: load ranges
The values of the load ranges obtained for the Friedrich-Kleinhans are higher, with no trend with the wind speed. For example, for 8m/s we have a mean of 107.9% and for 18m/s, 109.7%. See figures A3 and A4.

5.3. Resulting moment at the blade root: load ranges
The values for the Friedrich-Kleinhans model are higher for small wind speed and decrease to get lower for the higher wind speeds. For 5m/s, we have a mean of 107.6% and for 18m/s, 94.7%. See figures A5 and A6.

5.4. Tilt moment at the blade root: load ranges
The values for the Friedrich-Kleinhans model are lower with no trend regarding the wind speed. For 5m/s, the mean value of the load is by 11.1% lower, for 18ms by 13.9% lower. See figures A7 and A8.

5.5. Edgewise moment at the blade root: maximal values
The values for the Friedrich-Kleinhans model are lower and decrease with the wind speed from a mean of 89.1% for 5m/s to a mean of 82.7% for 15m/s. The highest moments from the 100 time series are lower for the Friedrich-Kleinhans model, with 90.9% for 5m/s to 96.6% for 15m/s. See figures A9 and A10.

5.6. Flapwise moment at the blade root: maximal values
The maximal values of the flapwise moment obtained for the Friedrich-Kleinhans decrease with the wind speed, from a mean of 104.3% for 8m/s to 96.6% for 15m/s. The maximal values of the maximal
flapwise moments tend to be higher but with no clear trend with the wind speed. We have for 8m/s a maximal moment by 12.2% higher and for 15m/s, 1.3%. See figures A11 and A12.

5.7. Resulting moment at the blade root: maximal values
The values for the Friedrich-Kleinhans model are higher for small wind speed and decrease to get lower for the higher wind speeds. For 5m/s, we have 102.4% and for 15m/s, 93.7%. The maximal value of the maximal moments gets lower from +3.4% for 5m/s to -0.9% for 15m/s.

5.8. Tilt moment at the tower top: maximal values
The maximal values of the tilt moment for the Friedrich-Kleinhans model are similar with no trend regarding the wind speed. For 5m/s, the mean value of the maximal moments is the same as for the Kaimal model, for 18m/s by 1.3% higher. The maximal values of the maximal moments are higher for the Friedrich-Kleinhans model, up to +14.8% for 12m/s compared to the Kaimal model.

5.9. Standard deviation
As far as the standard deviations of the loads are concerned, we have (nearly) always higher values for the Friedrich-Kleinhans model as for the Kaimal model. There is a trend of increasing standard deviations with the wind speed (in comparison to the Kaimal model). For example, in the case of the repartition of the load ranges of the resulting moment, the standard deviation is by 1.5% higher for 5m/s and 94.6% higher for 18m/s. Extreme values are met, e.g. for the tilt moment, where the standard deviation is by 221.7% higher for 18m/s.

6. Conclusion
From those results, it is not possible to make any definitive “higher-lower loads” conclusion. The edgewise moments are lower for the Friedrich-Kleinhans model as for the Kaimal model whereas the flapwise moments are higher. Concerning the resulting moment though, the loads show a trend of being higher for small wind speeds and lower for higher wind speeds. The tilt moment is for each case studied lower.

The results ought of course to be as much independent from the peculiar turbine used for the study as possible, in order to have as general conclusions as possible. This ideal case is, still, ideal and one should not neglect the effect of the control system. The values for the wind speeds around or higher than the rated wind speed of the D8 (13.5m/s) are therefore to be taken with caution when drawing conclusions. For example, the much higher value of the maximal value of the maximal resulting moments for the Friedrich-Kleinhans for 18m/s (+29.8%) is attributed to the regulation system. For 15m/s and 18m/s, the wind turbine can be shut down if the gusts get too high and it is this shutting down that can produce high loads that are not really representative of the model but rather of the quality of the regulation system.

The main conclusion that can be drawn from this study is that the non-Gaussian Friedrich-Kleinhans model produces loads that are significantly different from the loads obtained with the Kaimal model. That proves that the form of the tails of the increment distribution has a major influence on the loads of the wind turbine and should be considered when making fatigue calculations.

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Appendix A

Figure A1. Cumulated distribution of the load ranges of the edgewise moment, Vwind=5m/s.

Figure A2. Cumulated distribution of the load ranges of the edgewise moment, Vwind=18m/s.

Figure A3. Cumulated distribution of the load ranges of the flapwise moment, Vwind=5m/s.

Figure A4. Cumulated distribution of the load ranges of the flapwise moment, Vwind=18m/s.

Figure A5. Cumulated distribution of the load ranges of the resulting moment, Vwind=5m/s.

Figure A6. Cumulated distribution of the load ranges of the resulting moment, Vwind=18m/s.
Figure A7. Cumulated distribution of the load ranges of the tilt moment, $V_{\text{wind}}=5\text{m/s}$.

Figure A8. Cumulated distribution of the load ranges of the tilt moment, $V_{\text{wind}}=18\text{m/s}$.

Figure A9. Cumulated distribution of the maximal edgewise moment, $V_{\text{wind}}=5\text{m/s}$.

Figure A10. Cumulated distribution of the maximal edgewise moment, $V_{\text{wind}}=15\text{m/s}$.

Figure A11. Cumulated distribution of the maximal flapwise moment, $V_{\text{wind}}=5\text{m/s}$.

Figure A12. Cumulated distribution of the maximal flapwise moment, $V_{\text{wind}}=15\text{m/s}$.
Figure A13. Cumulated distribution of the maximal resulting moment, V\text{wind}=5m/s.

Figure A14. Cumulated distribution of the maximal resulting moment, V\text{wind}=15m/s.

Figure A15. Cumulated distribution of the maximal tilt moment, V\text{wind}=5m/s.

Figure A16. Cumulated distribution of the maximal tilt moment, V\text{wind}=18m/s.

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