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MULTIVARIATE STOCHASTIC METHODS FOR THE STRUCTURAL DESIGN OF WIND TURBINES

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Abstract. *In order to improve the structural design of steel towers for wind turbines, and in order to allow for detailed structural optimizations, a methodology is desirable which allows for quick and reliable considerations of the complex dynamic load situations. Whereat for the design of details for the machinery and the blade optimization time domain methods using multi-body-simulations are well established, their usage is often to extensive due to the needed level of detail to use them for an iterative tower design. Especially with regard to lattice towers, it is therefore desirable to investigate faster stochastic methods which focus on the overall dynamic behavior based on the probability of structural stresses within the tower construction. For this aim, in the present paper a modern stochastic concept is presented and results are compared to NRELS FAST algorithm.*

1 INTRODUCTION

The structural design of blades and the machinery of wind turbines are nowadays based on detailed transient dynamic calculations using multi-body systems (MBS) - which are doubtless indispensable for the construction of the machinery. But with respect to the design of the supporting structure, i.e. the tower and its foundation, the MBS models are unnecessary complex and the obtained results can therefore often only be taken in a simplified manner. With this load input, the design of the structure is carried out afterwards by means of individual calculations. As the dimensioning of the structural components influences the overall dynamic behavior of the wind turbine with respect to the aeroelastic load components and the inherent dynamic amplifications induced by the rotor, the design has to be iterative. With regard to the number of load cases and the time consumption of MBS simulations the structure is often not fully optimized, due to necessary simplifications.

In the field of wind engineering it is common practice to consider the complex stochastic wind load process on flexible structures by means of stochastic methods. An example of this methodology is the gust response factor approach given in Eurocode 1. Besides this simplified approach which is formulated for a single degree of freedom system, it is also possible to consider arbitrary multi-degree of freedom systems as long as the structural dynamic behavior can be treated linear. With application to wind turbines, this approach enables the necessary description of the correlated multivariate wind field and the formulation of the structural dynamic behavior of the response using complex spectral matrices. The main advantage is the algorithm is the allowance for a quick analysis of the load-response chain and to consider the structural interactions between the main components implicitly.

With the presented strategy, a design tool is introduced which especially focusses on the sup-porting structures of wind turbines taking into account the global dynamic behaviour and neglecting machinery details. Due to its faster usability, it might turn out as a useful tool for an optimized design of wind towers and foundations.

2 CONSIDERATION OF RANDOM LOADING

With respect to random loading, the response characteristic of structures is affected by the dynamic properties of a structural system. Dependent on the composition of the natural frequencies, mode shapes and on the damping behavior, the distribution of stress ranges and the maximum amplitudes at the structural details may vary significantly.

Due to the energy composition of the natural wind flow, especially slender structures with low structural frequencies tend to pronounced stress amplification due to this random process. Wind turbines are in particular slender, as their efficiency is highly dependent on hub height and the costs of the tower construction. The latter demands for strong optimization efforts which lowers the stiffness as far as possible. In consequence, wind turbines structures are highly prone to wind excited vibrations which have to be considered in the structural design and optimization process.

Generally there exist two concepts for the computation of structural responses due to random loading. The main difference is the domain in which the random loading is described. Basically, it is advantageous to describe random loads in a stochastic way as this allows for definite description of the turbulence contributions which form the wind speed on a given site. General recommendation for gust spectra are given e.g. in Eurocode 1. With respect to calculation of structural responses it is possible to remain in the stochastic domain or to switch over to the time domain. For the latter it is necessary to generate artificial wind fields. These fields are generally

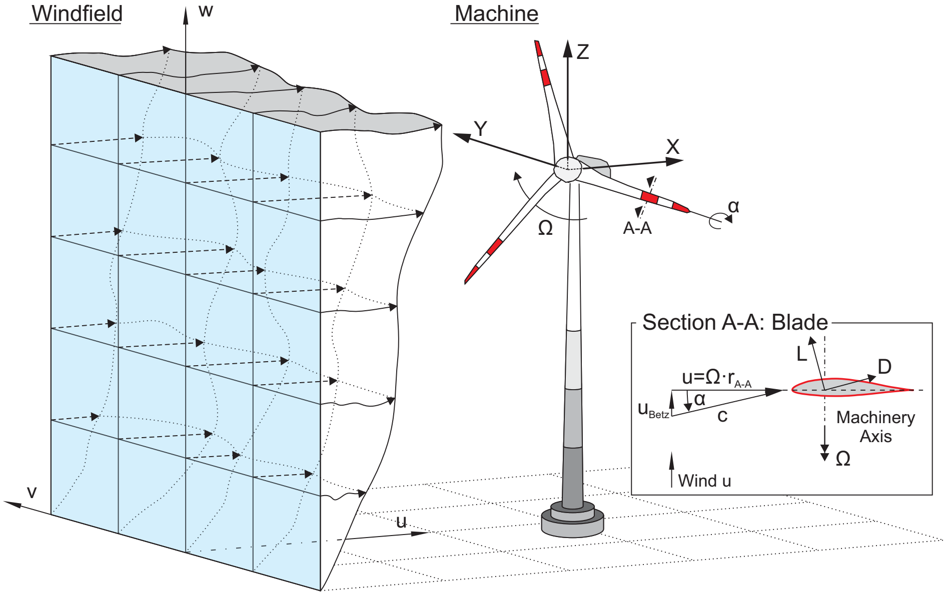

Figure 1: Definition of Axes and Directions of the Wind Turbine

only one representative of the stochastic description, for the needed statistical covering a higher quantity of wind fields has to be considered.

Time-based methods allow for very detailed calculations of the structural dynamic response. Furthermore they are able to consider structural non-linearities and the aeroelastic behavior of structural parts quite easy. With respect to wind turbines time based methods are therefore favored and in most cases performed using multi-body-simulations.

However, remaining in the stochastic domain is possible and it allows the prediction of the stochastic structural responses. Hence, as a result e.g. for the bending moment the spectral density can be obtained which allows the calculation of the statistical moments (e.g. the standard deviation). On a first look, this type of result is less ready to hand than having time series of the bending moment. But in opposite to the time based results, the knowledge of the statistical parameters is definite. Where the transient computations have to be repeated for multiple time-series of loading in order to allow an extreme value prediction, such statistical measures can be achieved directly based on the stochastic structural computation. Furthermore the stochastic method is much quicker, as it is mainly performed by matrix multiplications instead of time step integrations.

With stochastic concepts it is also possible to achieve the expected Rainflow distribution of structural stresses, which is an important measure for the verification of the fatigue stability. And again the method is much quicker the conventional time based procedure.

In the present paper a multivariate stochastic is presented which means that it is applicable for multi-degree of freedom systems. Due the described fast computation algorithm it is expected that the methodology may allow quicker structural optimizations in the future.

3 GENERAL DEFINITIONS

The Hub height of the investigated turbine equals to $H_{Hub} = 90$ m. A rotor diameter of $D_{Rotor} = 125.2$ m has been taken into account. In the study, a conical steel tower with an outer diameter of D_B=6.0m at the bottom and D_T=3.87m at the top respectively. As associated thickness values of T_B=27mm and T_T=19mm have been considered.

4 STOCHASTIC APPROACH FOR STRUCTURAL DESIGN OF WIND TURBINES

4.1 Wind Characteristics

For the description of the natural wind field, the reference values comparable to those of the NREL Study have been taken. The formulation of the resulting wind loading for the spectral method is described in the following subsections.

4.2 Spectral Description of the turbulent Wind Field

Due to the stochastic character of the fluctuating wind field, a general description succeeds with the power spectral density (PSD). In most standards, the *Kaimal* spectrum assuming neutral atmospheric stability has been implemented. For a single point in space with reference height z, the natural turbulence spectrum according to IEC 61400-1 [1] is defined as follows:

$$S_{UU}(f, z) = \frac{4.0 \cdot I_u^2(z) \cdot \overline{u}(z) \cdot L_{ux}(z)}{\left[1 + 6.0 \cdot \frac{f \cdot L_{ux}(z)}{\overline{u}(z)}\right]^{5/3}} \tag{1}$$

where: I_u = turbulence intensity, $\overline{u}$ = mean wind speed and L_{ux} = integral length scale in wind direction at the considered location. In order to take into account the spatial variability of wind speeds, it is common to take into account the coherence function which can be interpreted as the correlation measure of different spectra. According to Davenport [4], the vertical coherence can be expressed as:

$$\gamma_{i,j}(f, \Delta) = \exp\left\{-12.0 \cdot \sqrt{\left(\frac{\Delta \cdot f}{\overline{u}_{Hub}}\right)^2 + \left(0.12 \cdot \frac{\Delta}{L_c}\right)^2}\right\} \tag{2}$$

Where L_c = coherence scale parameter, Δ = spatial distance and $\overline{u}_{Hub}$ = mean wind speed at hub height. Although formula (2) principally only applies to the vertical coherence, it is common to use the formula for the entire spatial coherence, sometimes using adapted decay constants C. To formulate the full coherence relation, the matrix of spatial distances Δ is needed, where each item is defined as follows:

$$\Delta_{i,j} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \tag{3}$$

Using Eq. (2) and (3) the nxn coherence matrix $\underline{\gamma}(f)$ for a point vector with n-entries with respect to the flow direction can be assembled.

As the diagonal elements of the distance matrix $\underline{\Delta}$ equal to zero, the diagonal coherence elements are unique. Using the coherence relation, the wind field can be expressed as a nxn-spectral density matrix of wind turbulence as follows:

$$\underline{S}_{UU}(f) = \underline{\gamma}(f) \cdot S_{UU}(f) \tag{4}$$

The formulation of a symmetric gust spectrum neglects phase shifts, which have been reported during on-site measurements. In most cases, this disregardance should be of minor effect on the load formulation. Furthermore, realistic measures for certain locations are not available in the literature.

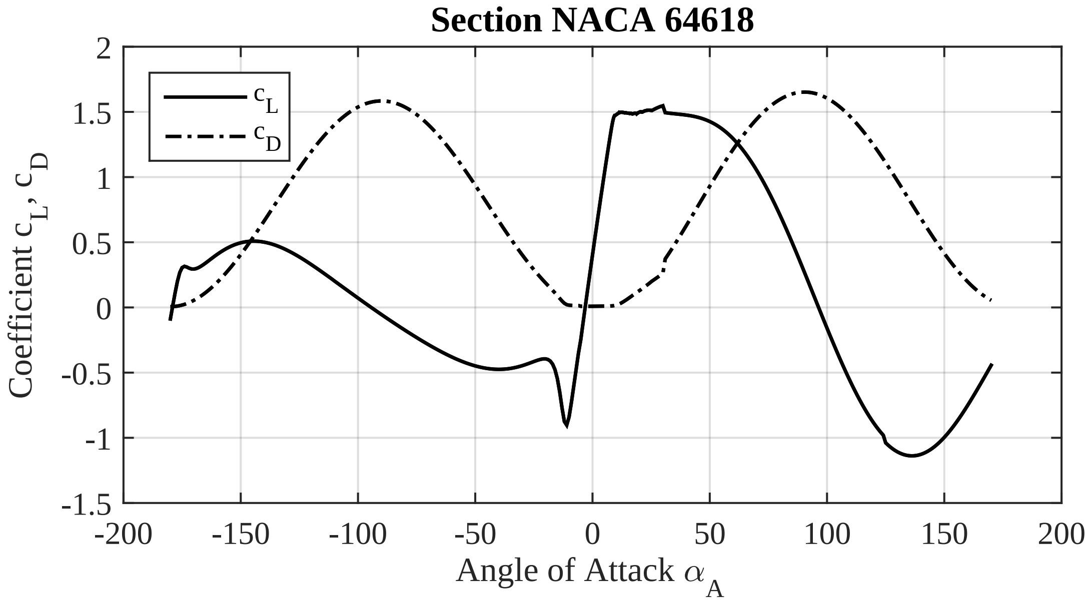

Figure 2: Aerodynamic Coefficients depend on the angle of attack, Exemplary curves of the NACA 64816 profile which is used at the outher third of the blades, here at $Re = 1 \cdot 10^6$

4.3 Aerodynamic Admittance

Wind loads on structures are generated due to a variable pressure fields, distributed over the entire surface. The approaching wind field and rather the individual wind vector at a structural point is responsible for the shape of the resulting pressure distribution at the associated structural section. The integrated pressure distribution leads to the instantaneous wind forces. With respect to line-like structures like the tower sturcture and the blades of wind turbines, it is common to define aerodynamic force coefficients, which can be interpreted as the integral directional wind forces, related to the approaching velocity pressure and normalized to a geometrical measure. The force coefficients are denoted as c_D, c_L and c_M, related to the drag, lift and moment forces and oriented to a wind-fixed coordinate system.

The force coefficients for all blade profiles have been calculated for various Reynolds numbers and angles of attack with the software QBlade [6] using the outer shape polygons. As the force admittance depends on the actual aerodynamic angle of attack α_A and the Reynoldsnumber Re, the values are interpolated appropriately.

For simple cases it is sufficient to formulate a stationary admittance approach, meaning that the time variability does not affect the resulting forces. Actually, with increasing frequency of force attack, the resulting force amplitudes are decreasing, as the spatial extent of the wind gusts are decreasing and consequently the correlation measure decreases as well. This effect is denoted as instationary aerodynamic admittance and considered by the coherence relation according to Eq. (2).

Due to the possible large vibrations, especially of the turbine blades, aeroelastic effects become relevant. In time based calculations it is possible to use the time related relative wind speeds to obtain a realistic aerodynamic damping behavior. Alternatively and suitable for usage with spectral methods, an analytical expression Kuehn [5] can be used:

$$\xi_{Aero} = \frac{3 \cdot \rho_{Air} \cdot \Omega}{8 \cdot \pi \cdot f_0 \cdot M_0} \int_{R_{root}}^{R} \frac{\delta c_l(r)}{\delta \alpha(r)} \cdot c(r) \cdot r \, dr \tag{5}$$

where: Ω = rotational speed of rotor, f_0 first along wind bending mode frequency, M_0 = associated modal mass, $\delta c_l/\delta\alpha$ = slope of lift coefficient with respect to angle of attack and $c(r)$ = chord length at radius r.

Eq. (5) is based on stationary rotor aerodynamics and considers some simplifications concerning the tip speed ratio.

4.4 Blade Aerodynamics

Blades of wind turbines are specially designed with respect to the rotor diameter and the expected wind speed distribution on sited. In this paper the aerodynamic blade properties are taken in dependence on the NREL 5-MW Reference Wind Turbine [2]. The blade sections are defined in table 1.

Table 1: Blade Aerodynamic Characteristics

Blade Section	Start-Pos [m]	End-Pos [m]
DU99W405LM	0	13.07
DU99W350LM	13.07	20.54
DU97W300LM	20.54	24.28
DU91W225LM	24.28	31.75
DU93W210LM	31.75	39.22
NACA 64618	39.22	61.63

For the detailed description of the blade properties reference is made to the NREL report [2]. In the present study, the aerodynamic coefficients for the blade profile sections have been computed with QBlade [6] for various angles of attack α_A and for different Reynolds numbers Re. In Figure 2, some exemplary force coefficients for two blade sections are illustrated.

For the computation, the blades have been discretized in 17 sections, the loads are induced at 16 aerodynamic nodes. For later calculations, the discretization can be simply increased. The aerodynamic properties of turbine blades dependent on the angle of attack and the Reynolds number Re. The presented stochastic computation method has been implemented in Matlab. The code automatically assigns the appropriate aerodynamic coefficients to the aerodynamic blade sections, dependent on the angle of attack and the current Reynolds number, which is computed based on the individual chord lengths and the mean nodal wind velocity.

The power spectral density of the acting wind force is expressed as spectral density matrix $S_{FF}(f)$, where the indiviual items can be obtained as follows:

$$S_{FF,ij}(f) = S_{UU,ij} \cdot \rho_{Air}^2 \cdot \overline{u}_i(z) \cdot c_{f,i}(\alpha_A, \Omega, Re) \cdot A_i \cdot \overline{u}_j(z) \cdot c_{f,j}(\alpha_A, \Omega, Re) \cdot A_j \quad (6)$$

Based on the spectral density matrix of the wind forces, the instationary wind loading can be described for each DOF of the model. With respect to the necessary consideration of the individual angles of attack, the rotation speed and the Reynolds number, the admittance function has to be updated for each step in rotational discretization.

4.5 Mechanical Properties of the Structural System

Both, blades and tower have been modeled elastically with realistic bending stiffness. However, occurring aeroelastic effects have been neglected in this first setup. The chosen approach allows for a direct computation of the stationary and instationary rotor loading using the coherence matrix of wind forces at the aerodynamic nodes of the blades. The stiffness matrix K has been set up based on three-dimensional beam elements with the full set of 12 DOF per element. With the prepared algorithm within Matlab, the discretization density of the tower and blade structure can be adjusted individually.

A corresponding mass matrix M has been assembled considering the transversal masses associated with the model nodes. Using a Rayleigh model, a damping Matrix D has been assembled based on a linear combination of mass and stiffness matrix.

$$\underline{D} = \alpha \cdot \underline{M} + \beta \cdot \underline{K} \tag{7}$$

Where the Parameter and are the Rayleigh coefficients, calculated based on two arbitrary frequencies and the desired damping ratio ξ. Due to the resulting frequency dependent characteristic of the obtained damping behavior, it is meaningful to fit the Rayleigh coefficients in order to match the damping ratio at the most relevant Eigenfrequencies. For further explanation reference is made e.g. to [6].

Using all structural matrices, the complex mechanical admittance function can be computed:

$$\underline{H}(f) = \frac{1}{-\left(2\pi f\right)^2 \cdot \underline{M} + i\underline{D} + \underline{K}} \tag{8}$$

The complex spectral admittance function of a system includes the complete structural information, including element wise damping and single damping elements (in contrast to the modal analysis concept). In Figure 3, the admittance function is plotted for the computed system.

4.6 Structural Responses of the stopped Machine

Based on the turbulent wind field, the aerodynamic and the mechanical admittance, the stationary and instationary responses of the stopped can be calculated using a multivariate stochastic approach. The spectral density matrix $S_{RR}(f)$ can be computed as follows:

$$\underline{S}_{RR}(f) = \underline{H}(f) \cdot \underline{S}_{FF}(f) \cdot \underline{H}(f)^T \tag{9}$$

The spectral density of the wind loading in this study only comprises the drag load, which is most decisive for the structural design of the supporting tower.

As described in section 2, the usage of a stochastic computation method allows for a full set of all statistically relevant response measures. All results are available within the resulting density matrix of structural deflections $\underline{S}_{RR}(f)$. Based on the mechanical admittance of the structural system, the corresponding frequencies of occurrence of inner forces and stresses can be obtained.

The calculations have been made for $N_f = 500$ frequency steps with a logarithmic spacing between f=0.01 Hz and 10 Hz. The algorithm allows the computation of arbitrary rotor positions Ω and pitch angles Θ.

4.7 Consideration of Operational States

A special challenge is the consideration of the operational states in the stochastic algorithm. The influence of the blade rotation is determined based on calculations for different rotor angles . Dependent on the rotation, the single blade elements are loaded variably due to the changing average wind velocities and turbulence contents with height. In Figure 4, the resulting tip displacement is plotted over the rotation angle . Due to the consideration of three blades, the relative variability of the out of plane displacement at the top of the tower is much less. However, the periodic load distribution is vulnerable when tower Eigenfrequencies are affected. In Figure 5 the admittance function of a blade tip is plotted over the rotational angle. As the stiffness of the tower support varies dependent on the rotational position, the admittance function is not unique with respect to .

Dependent on the load variability and the angular speed, the periodic load contribution can be calculated. In consequence, a modified stochastic load case is generated which can be superimposed with the load set of a stationary rotor.

5 TIME DOMAIN APPROACH

Time domain calculations have been performed using the FAST program [4]. Wind fields have been computed using TurbSim [3] for different average wind speeds. All settings have been made in accordance the the NREL reference wind turbine [2]. Only the description of the gust spectrum has been formulated divergent (IEC 61400-1 instead of smooth).

The FAST algorithm allows the fully aerodynamic and aeroelastic calculations of a pitch-controlled wind turbine. Various response measures can be chosen for the output files. In this paper the dynamic responses of the tower are mainly focused. In Figure 3, the time related results for the tower deflections are plotted.

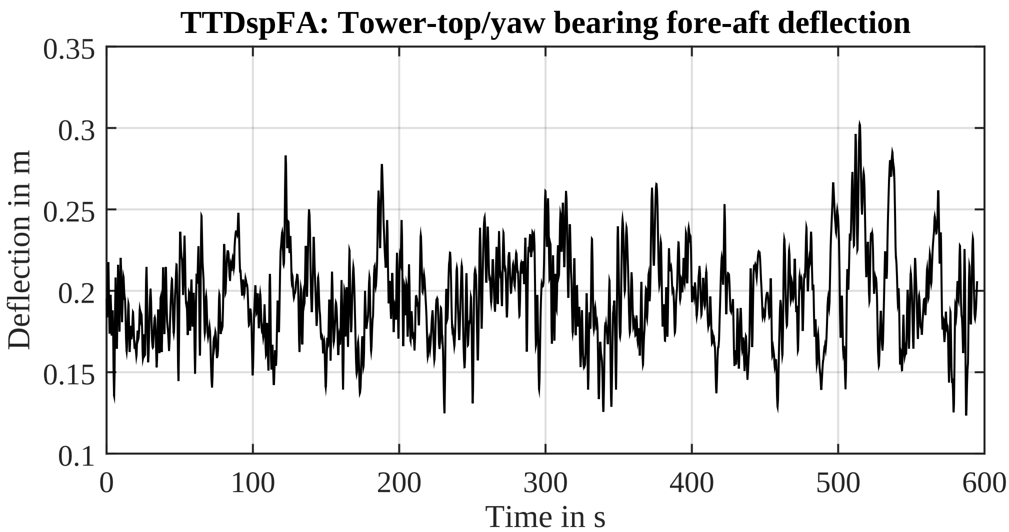

Figure 3: Exemplary Time Series of Tower Deflection, Operation Wind Speed of $v_{Hub} = 18$ m/s

For the design of tower structures the dynamic response at the top of the tower is the most important measure. Therefore, in the following section the corresponding frequency-related results are compared.

6 COMPARISON OF RESULTS

Simulation with FAST have been performed for four different mean wind speed at hub height: $v_{Hub} = 9$ m/s, $v_{Hub} = 14$ m/s, $v_{Hub} = 18$ m/s and $v_{Hub} = 27.5$ m/s. The FAST simulations considered a pitch-control algorithm (conventional variable speed, variable blade-pitch-to-feather configuration). The resulting average rotational speeds have been used for the stochastic computations at the same average wind speeds.

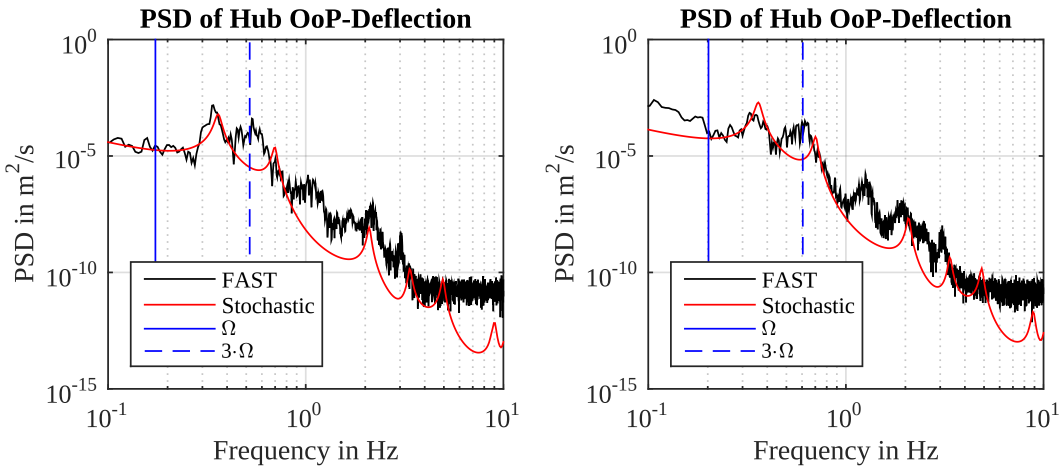

Figure 4: Along-wind Hub Deflection: Operation Wind Speed of $v_{Hub} = 9$ m/s (left) and $v_{Hub} = 14$ m/s (right)

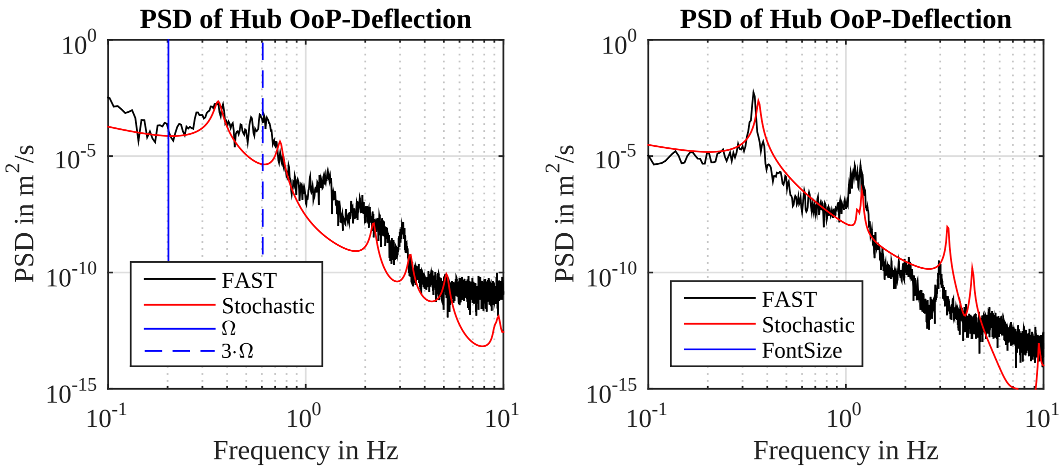

Figure 5: Along-wind Hub Deflection: Operation Wind Speed of $v_{Hub} = 18$ m/s (left) and Cut-Out Wind Speed of $v_{Hub} = 27.5$ m/s (right)

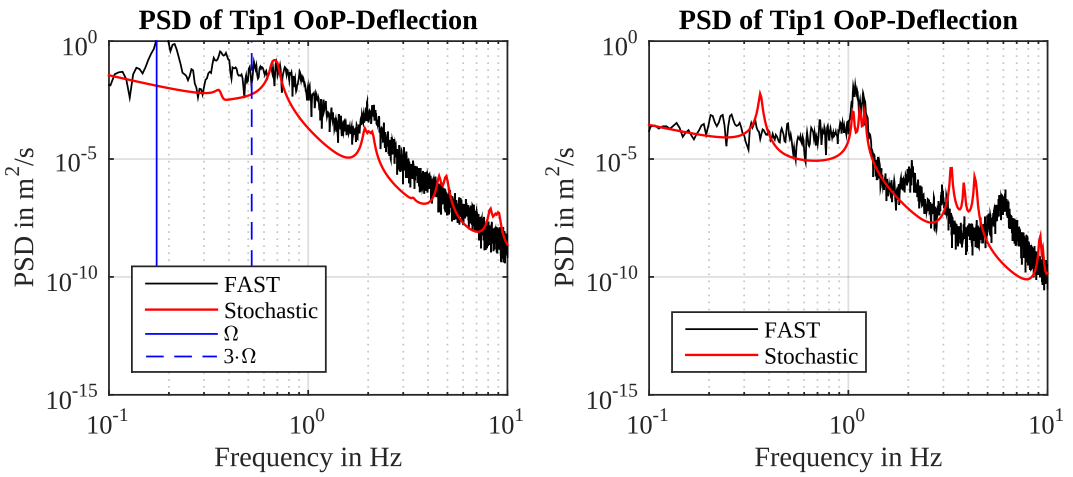

Figure 6: Along-wind Tip Deflection of Blade 1: Operation Wind Speed of $v_{Hub} = 9$ m/s (left) and Cut-Out Wind Speed of $v_{Hub} = 27.5$ m/s (right)

In order to allow a comparison of results, the resulting time series of the FAST algorithm have been analyzed with respect to its frequency domain content. Therefore a windowed spectral analysis has been made using a Hanning-window with a length of one fourth of the total simulation time. Due to the sudden loading at the beginning of the simulation the first 30s of the simulation time has been neglected for all further analyzes (and in the figures as well).

The comparison of the obtained result are presented in Fig. 4 till 6. Aside from the rotational frequency Ω and its multiple (this effect is not implemented yet), the general decay trend and most Eigenfrequencies are represented quite satisfactory using the stochastic method. The spectral sum, which represents the variance of the response process, is comparable.

7 CONCLUSIONS

For a possible future usage of spectral methods for the optimization of tower structures, the computation of structural responses of 3 bladed wind turbine has been performed in the time and the frequency domain. For the former, the well established FAST algorithm has been used. For the latter, a multivariate stochastic approach has been implemented in the programming environment of Matlab. The computation time with FAST averages out at some minutes (which is already extremely fast for a time domain algorithm) whereat the stochastic approach only takes seconds.

The structural and aerodynamic properties have been taken from the 5MW NREL reference wind turbine. Simplified assumptions had to be made for the aeroelastic behavior of the blades in the frequency domain. Furthermore, some inaccuracies remained in the stochastic model with respect to the structural detailing (rotary inertia of hub and nacelle), the eccentricity of the center of masses and the lateral gust components have been made. Additionally, a unique Rayleigh Damping has been assumed. Finally, the stochastic gust model in the present study is just one-dimensional at the moment. Lateral gust components should be included in future work. The mentioned improvements will certainly lead to a further increase of model reliability.

Currently, the stochastic approach considers rotating blade positions but it neglects the periodic loading which is caused by this rotation (Ω and $3 \cdot \Omega$ load contributions). For this aim, an analytical approach will be implemented in further developments.

Results have been obtained in the frequency domain for discrete rotor angle positions Ω. The average power spectral densities of the associated hub displacements have been compared to the results of the operating state based on the FAST calculation.

The obtained structural responses of the tower show wide banded contributions in a range of f =0.3 to 3 Hz. Fundamentally, the multivariate stochastic approach is able to predict the tower responses with respect to the average spectral magnitude and the location of natural frequencies with satisfactory precision. The major aim, a quicker analytical method to estimate dynamic responses for an improved structural optimization, seems reachable. Especially with regard to lattice towers, it seems to be helpful in combination with stochastic optimization algorithms. However, further incorporation of modeling details is necessary.

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