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SIMPLIFIED AERODYNAMIC LOADING MODEL FOR NON-PRODUCTION CONDITIONS FOR FLOATING WIND SYSTEMS DESIGN

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ABSTRACT

Floating wind is now entering a commercial-stage, and there are a significant number of commercial projects in countries like France, Japan, UK and Portugal. A floating wind project is complex and has many interdependencies and interfaces. During all stages of the project several participants are expected to use a numerical model of the whole system and not only the part the participant has to design. Examples of this are the mooring and floater designer requiring a coupled model of the whole system including also the wind turbine, the operations team requiring a model of the system to plan towing and operations. All these stakeholders require a coupled model where the hydrodynamics, aerodynamics and structural physics of the system are captured with different levels of accuracy.

In this paper, we will concentrate on a simplified model for the aerodynamic loading of the turbine in idling and standstill conditions that can be easily implemented in a simulation tool used for floater, mooring and marine operations studies.

The method consists of using a subset of simulations at constant wind speed (ideally close to the wind speed required for the simulations) run on a detailed turbine model on a rigid tower and fixed foundation - normally run by the turbine designer. A proxy to the aerodynamic loads on the rotor and nacelle (RNA) is to take the horizontal yaw bearing loads. The process is then repeated for a range of nacelle yaw misalignments (for example every 15° for 360°). A look-up table with the horizontal yaw bearing load for the range of wind-rotor misalignments investigated is created. The simplified model of the aerodynamic loads on the RNA consists of a fixed blade (or wing) segment located at the hub, where aerodynamic drag and lift coefficients can be specified. Using the look-up tables created using the detailed turbine model, drag and lift coefficients are estimated as a function of the angle between the rotor and the wind direction.

This representation of the aerodynamic loading on the RNA was then verified against full-field turbulent wind simulations in fixed and floating conditions using a multi-megawatt commercial turbine. The results for the parameters concerning the floater, mooring and marine operations design were monitored (e.g. tower bottom loads, offsets, pitch, mooring tensions) for extreme conditions and the errors introduced by this simplified rotor are generally lower than 4%. This illustrates that this simplified representation of the turbine can be used by the various parties of the project during the early stages of the design, particularly when knowing the loading within the RNA and on higher sections of the tower is not important.

Keywords: Floating wind, coupled simulation, simplified, reduced model, idling, parked.

NOMENCLATURE

α	Angle between the rotor and the wind
ρ	Wind Density
C_L	Lift Coefficient
C_D	Drag Coefficient
H_S	Significant wave height
T_P	Peak Period
C	Chord of the reference blade element
L	Length of the reference blade element

INTRODUCTION

Floating offshore wind turbine (FOWT) engineering requires coupled time-domain simulation of the entire system (wind turbine generator + floater + moorings) subjected to wind, waves, and currents (see for instance DNVGL [1]). Simulation outputs such as motions and component loads are used at each design iteration to converge on a product architecture and employed again at the end of the process to verify its integrity. Whilst it is required for final verification to represent all the parts of the system in an explicit way in the simulator, in early project stages or dedicated sensitivity studies it is possible to simplify parts of the model for ease of setup, speed, or data availability reasons.

More specifically, from a platform/mooring designer point of view, it is advantageous to have a way of running simulations without detailed information about the wind turbine generator (WTG) and especially the rotor-nacelle assembly (RNA), including blade sectional data and the controller; the latter are not easily shared across industrial partners at early project stages. This aspect has been tackled by past studies with typical focus on representing gyroscopic loads and/or the rotor thrust associated to **production** conditions, often with care not to introduce undue negative damping above the rated wind speed. Most of the times, for the aerodynamic part, the blade element and momentum (BEM) theory is replaced by passive models relying on the incident wind field and calibrated thrust/torque coefficients. Examples of this type are found in Karimirad and Moan [2], Utsunomiya et al. [3], Féron et al. [4], Olondriz et al. [5], and Dinh et al. [6] for the floating application. Pegalajar-Jurado et al. [7] concentrate on the reduction (linearization) of the reactive aerodynamic loads responsible for global aerodynamic damping. Finally, Smilden et al. [8] focusses on unsteady effects and wind field sampling affecting a bottom-fixed reduced model.

So far, the specific problem of simplifying a WTG model for idling and **parked** cases has not seen comparable development; a readily available publication explicitly mentioning it is a poster by Beyer et al. [9]. Yet, surviving extreme loading conditions with a parked turbine such as the IEC ULS 6.1 family is often a critical design driver. In such situation, turbulent-wind aerodynamic loads are exerted on the superstructures: drag-based windage can be easily applied on the floater, tower and nacelle components using a conventional building block approach (see for example Walree and Willemsen [10]). In a full FOWT model, aerodynamic loads on a parked rotor still derive from application of the BEM theory, typically reduced to a special case with the induction, dynamic stall, and dynamic inflow models disabled (see for example [11]). In such configurations, the blade profiles still attract significant aerodynamic loads; in particular, for 6.1 type cases where the blades are correctly feathered, lift-related lateral loads responding to turbulent wind features are quite lively and able to introduce significant global dynamic responses. Without a complete description of the blades, it is hence difficult to obtain accurate outputs; the goal of the presented method is to restore this ability based on a reduced aerodynamic calibration using only high-level (integral) RNA aerodynamic data from the wind turbine designer.

MODEL DESCRIPTION

For the simplified model (termed as I1) the horizontal aerodynamic loadings on the RNA are modelled as the aerodynamic loading on a single, small blade element using drag (C_D) and lift (C_L) coefficients. The aerodynamic coefficients are calibrated so that to represent the full loading aerodynamic on the RNA. A diagram of the blade element is shown in Figure 1.

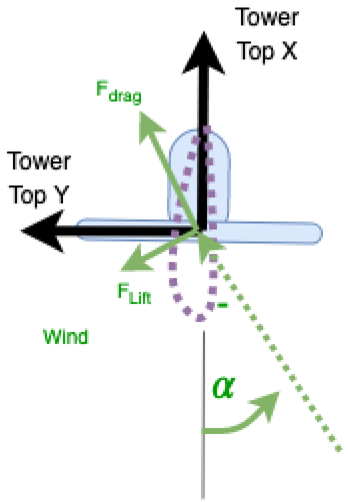


FIGURE 1: AERODYNAMIC FORCES ACTING ON THE MODEL. TOWER TOP REFERENTIAL AND AERODYNAMIC FORCES ON THE SINGLE BLADE ELEMENT.

The calibration process for the drag and lift coefficients to be used in the simplified model is as follows:

- Run full fixed (aeroelastic) turbine model for a range of yaw errors (rotor to wind direction misalignments). Here 15° intervals from 0° to 360° are suggested. The wind speed is constant and the simulation length should be enough to make any transients disappear.
- Wind shear should be considered in the simulation. And the rotor should be idling or parked depending on the desired state of the turbine.
- Analyse the aerodynamic loading of the components of interest. In this case tower top / yaw bearing will be considered - this means aerodynamic loading in the nacelle will be included in the polar coefficients.
- For a given wind to rotor direction misalignment, decompose the tower top loads horizontal loads (mean) in the lift and drag reference frame (drag aligned with relative wind direction) - **FIGURE 1**.

The aerodynamic coefficients are calibrated based on the decomposition of the yaw bearing forces on the fixed turbine. The lift (F_{Lift}) and drag forces (F_{Drag}) acting on the blade element of the simplified model, can be calculated using the lift and drag coefficients

$$F_{Lift} = \frac{1}{2}\rho\, C_L U^2\, C\, L \qquad (1)$$

$$F_{Drag} = \frac{1}{2}\rho\, C_D U^2\, C\, L \qquad (2)$$

Where, ρ is the air density, U is the wind speed, C is the blade element chord and L the element length (here taken as unit).

The aerodynamic forces can be calculated using the tower top horizontal forces (F_x and F_y)

$$F_{Drag} = F_x \cos\alpha + F_y \sin\alpha \qquad (3)$$

$$F_{Lift} = -F_x \sin\alpha + F_y \cos\alpha \qquad (4)$$

Then C_D and C_L can be calculated based on the equation (1) and (2), for the range of wind/rotor misalignments directions considered.

The aerodynamic coefficients calibrated are then assigned to the simplified turbine model. The following steps should be done:

- The calculated C_D and C_L are added to a non-rotating blade element located at the hub location of the turbine.
- All aerodynamic load sources for the RNA need to be removed.
- The mass properties of the blades and RNA can be added using a distributed model, or a lumped mass matrix.

This model is a representation and there are elements that are not considered in detail, such as the aerodynamic created moments, eventual rotation of the rotor. The reader should be reminded that the objective of this model is to create a model useful for platform/mooring design. Its suitability will be assessed in the next sections.

VERIFICATION

Next a verification is presented to show that the new simplified model is a good representation of the RNA aerodynamic loading. The verification of the model was performed in fixed condition to make sure the horizontal loading at the tower top was reproduced in the simplified model.

For the fixed turbine the verification of the implementation was carried out by:

- Comparing the turbine aerodynamic loads calculated by the I1 method and the original data used for calibration – to check that the implementation in the software was correct.
- Use turbulent wind runs and compare the aerodynamic loads between the simplified and the fully defined turbine provided in bottom-fixed condition. The objective is to assess the accuracy of the method focusing only on the aerodynamic forces.

Turbine and model used

For this paper a generic Multimegawatt (5MW+) turbine was used. The full numerical turbine model was created in an aeroelastic software based on NREL FAST [12] used by Naval Energies. Some generic information about the turbine can be found in Table 1.

TABLE 1: WIND TURBINE MODEL.

Number of blades	3
Hub height	~105m
Rotor diameter	~160m
Rotor + hub mass	~150 000 kg
Machine condition	Idling

Coefficient calibration

The methodology described above was used to estimate the C_D and C_L coefficients needed to create the simplified model. The aeroelastic time domain simulations were run using constant and homogeneous wind speed at 40.5 m/s. Figure 2 depicts the resultant C_D and C_L coefficients .

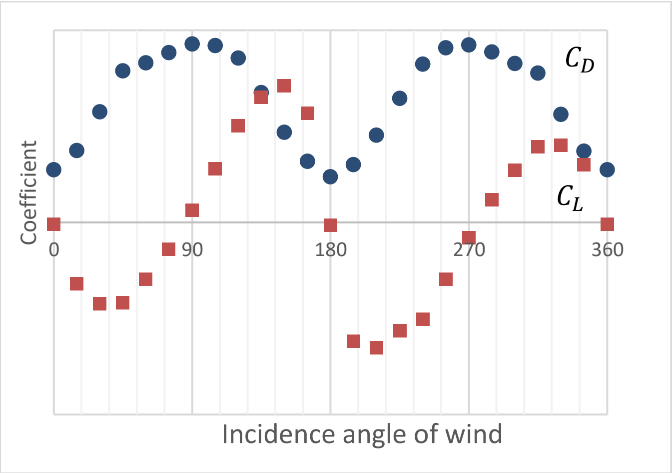


FIGURE 2: C_D AND C_L FOR A RANGE OF WIND INCIDENCE ANGLES.

Using the coefficients from the calibration in Figure 2, the yaw bearing loads at the tower top were compared for the simplified I1 model and the full model. The comparison for a constant wind speed of 40.5 m/s and a range of rotor to wind direction of 360° is shown in Figure 3. A very good agreement between the models is shown indicating the good implementation of the simplified model.

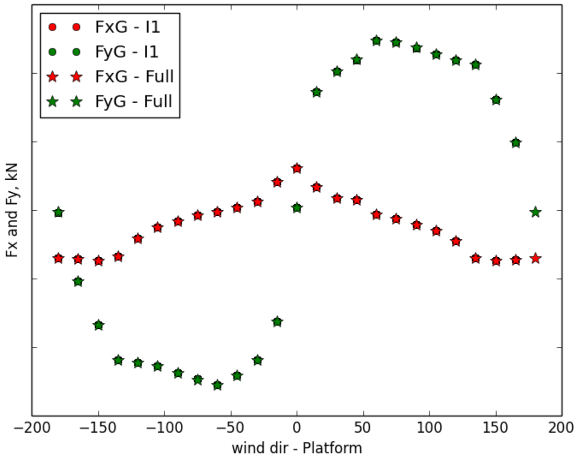


FIGURE 3: I1 AND FULL TURBINE MODELS – MEAN FORE-AFT (F_x) AND SIDE-SIDE FORCES (F_y) (0° MEANS WIND ALIGNED WITH THE $X - AXIS$). CONSTANT WIND.

Turbulent wind

The verification exercise was extended using full-field turbulent wind. A mean wind speed of 40.5m/s with a Turbulence Intensity of 11% was used for this comparison. The turbine was fixed and the tower of the simplified model was rigid, whereas the fully represented WTG model was flexible. As above we will be focusing on the tower top loading as we are mostly interested in assessing the accuracy of the method implemented. Figure 4 has the horizontal forces time-series and spectral results for the wind and rotor aligned case. The two models have differences as expected, but the global behaviour is similar, albeit a slightly lower high frequency content on the simplified model with the rigid tower.

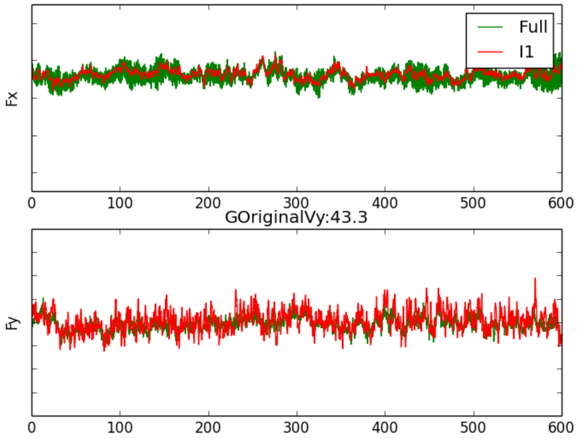


FIGURE 4: I1 AND FULL TURBINE FORE-AFT (F_x) AND SIDE-SIDE FORCES (F_y). ALIGNED TURBULENT WIND CASE.

Figure 5 shows the mean tower top forces for turbulent wind for different tower top rotor to wind speed direction misalignments. A good agreement for all load components and directions considered is registered.

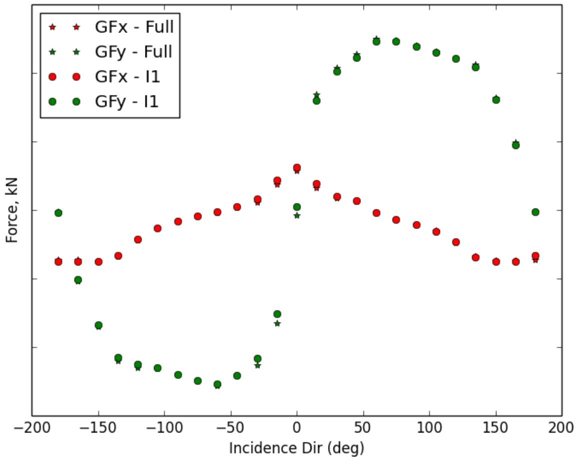


FIGURE 5: I1 AND FULL TURBINE MODELS - MEAN HORIZONTAL FORCES AT TOWER TOP FOR A RANGE OF WIND DIRECTIONS. 40.5 M/S TURBULENT WIND.

FLOATING TURBINE APPLICATION

The real interest of this method is to have a simplified representation of the aerodynamic loads on the RNA represented in coupled simulations of a floating wind turbine. And the outputs of such simulations are to be used in floating platform and mooring system design. To assess the applicability of this type of approach on a floating turbine, a verification study was carried out, comparing some important variables on the floater and mooring system calculated using a simplified and the complete model.

Study inputs

The system used for this test was a NE semi-submersible floating wind turbine platform denoted "Star1" with a 5+MW wind turbine installed. Some generic data on the platform can be found in Table 2. A diagram of the floating system is also illustrated in Figure 5.

TABLE 2: FLOATING WIND PLATFORM AND SITE DATA.

Number of pontoons	3
Pontoon length	~41m
Draft	~20m
Water depth	~60m
Hub height	~105m
Number of mooring lines	5
Mooring layout	3 lines facing up-wind on the exposed side. 2 lines on the sheltered side

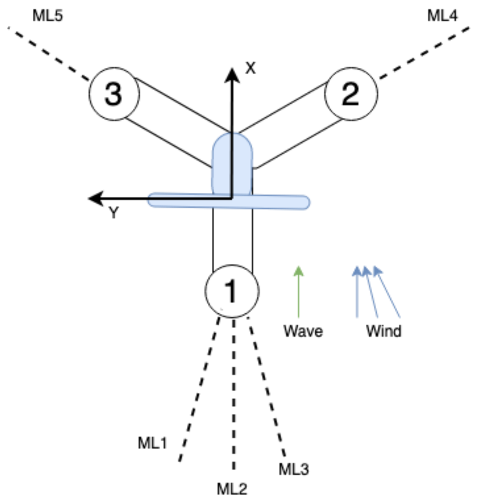


FIGURE 6: SKETCH OF THE WIND TURBINE, FLOATER, MOORING LINES AND MAIN COORDINATE SYSTEM.

The 3 load cases considered are summarized in Table 3. The conditions are representative of extreme conditions found in a generic site off the Atlantic French coast. The sole difference between load cases is that wind direction misalignments to the wave direction of 0°, 15°, and 30° were considered. The current direction is aligned with the wind direction. The simulated wind and wave directions are also illustrated in Figure 5. Six different wind and wave seeds per load case were run with RNA yaw errors (with respect to the mean wind direction) evenly distributed within the seeds (-8°, 0°, and +8°). The same wave and wind realisation was used for the simplified and the full turbine models. A selected wave with $H_{max} = 1.89\ H_s$, was considered in the middle of the 3600s simulation (1800+600s). A 600s ramp-up period was used upfront.

The time domain results for the tower bottom overturning moment (M_y – perpendicular to wave propagation), M_x, Platform pitch, and the tension on the central line of the exposed side are illustrated in Figure 5. From these results, the tower base moments are quite well represented using the simplified method. Clearly the wind loading is not a driving factor for the tower bottom overturning moment (M_y) under extreme conditions. The discrepancies at the tower top loading observed in the fixed model and the lack of some aerodynamic loading components (namely Aerodynamic moments) have a small impact on this load component. Similar conclusions can be drawn for the mooring tensions.

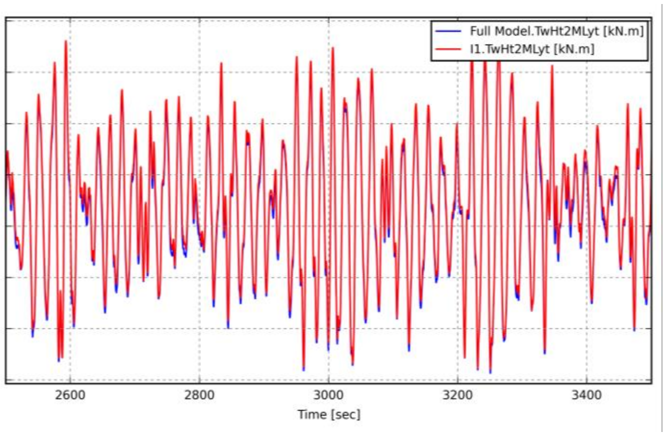
TABLE 3: LOAD CASES USED FOR THE FLOATING MODEL VERIFICATION FOR A GENERIC ATLANTIC SITE (JONSWAP SPECTRA).

#	H_s	T_P	Wave Dir	Wind Speed	Wind Dir	Number of seeds
-	[m]	[s]	[deg]	[m/s]	[deg]	-
1	11	17.2	255	40.5	255	6
2	11	17.2	255	40.5	270	6
3	11	17.2	255	40.5	285	6

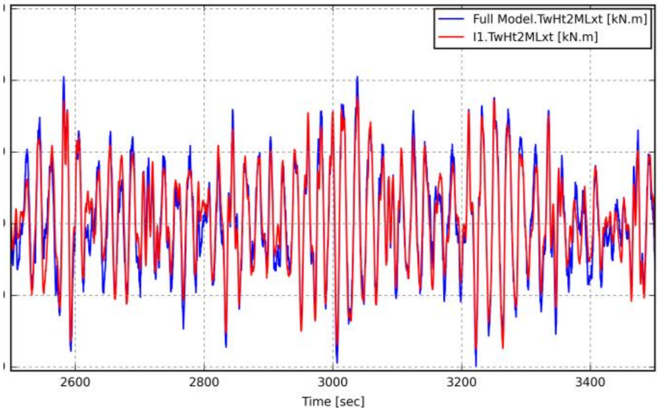
Results

The results for all the load cases were compared initially case by case, and then the extreme values observed throughout all the simulations were also analysed. The mean of max results for the 6 seeds was calculated for each of the cases run to synthesise characteristic ULS loads. The simplified and the full turbine model extreme results are provided below in Table 4. The forces at the tower top show very good agreement, indicating the suitability of the method. However, the difference in the moments at the tower top is quite large (~40%) which was expected, given the simplified model disregards those aerodynamic load components.

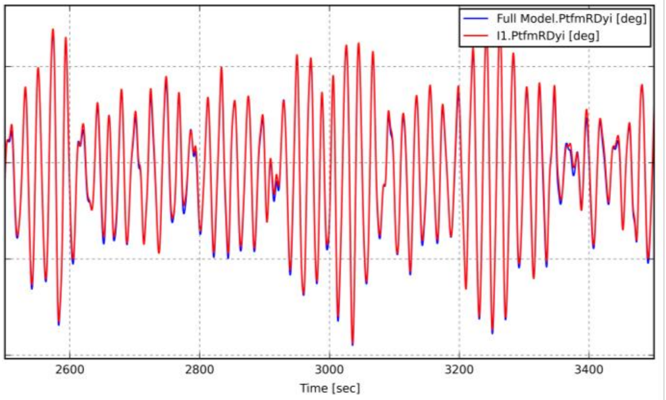
A good agreement is observed for all the variables relevant for the platform and mooring designer, with very small differences. A maximum difference of 2% is observed in the absolute bending moment at the tower bottom when each load is compared separately. And the maximum bending moment observed is underpredicted by 3% with the simplified model. The platform pitch and nacelle acceleration also show a good match.



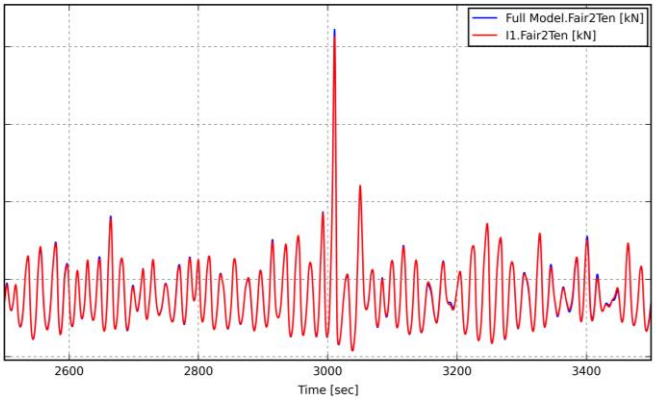
a) Tower Bottom M_y (perpendicular to wave)



b) Tower Bottom M_x ()



c) Platform Pitch



d) Mooring line #2 tension

FIGURE 7: TIME SERIES FOR THE I1 AND FULL MODEL FOR THE LOAD CASE #3 (Red line - I1 method, Blue Line – Full model).

The moorings lines 1,2 and 3 are also quite well represented with the simplified model presented here. A larger discrepancy is registered for mooring lines 4 and 5 with and under and over prediction of 6% respectively. But the cases reported here are most likely not the driving cases for the design of these lines: the tensions observed here are much smaller than those found for waves aligned with line 4 and 5; so these large differences are noticed because the tension values are quite small. Similar observations are made for the side-side forces at the tower top, F_y . Again, this component is very small when compared with the fore-aft component aligned of the tower top. The large errors presented in the tower top F_y are not expected to be important for the behaviour and loading of the structure.

The results for the 3 different wind directions are quite similar, and the model seems to behave well for the different wave to wind misalignments.

These results show that the influence of the wind loading on these driving ultimate load cases is drastically reduced for the load components closer to the platform. And a simplified model can be used to model these cases where the turbine is not operating.

The standard deviation of the tower overturning moment is summarized in **TABLE 5**. A good agreement on the tower bottom standard deviation is also seen for these 3 load cases, a difference of 2% registered. This results also provide a good indication on the applicability of the method for the fatigue calculation of the idling cases.

CONCLUSION

This paper describes a simplified modelling approach for wind turbine rotor and nacelle aerodynamic loading, denoted I1. It was seen that the present method is a good representation of the RNA loading for applications where the wind loading is not the main driver. This method seems to be particularly suitable to include RNA aerodynamic loading on numerical analysis of a floating wind platform and mooring line analysis for non-production states.

The method consists of using C_D and C_L curves as function of the mean wind to rotor misalignment to match the full turbine RNA aerodynamic loading. The method was verified on a fixed turbine comparing the horizontal forces at the tower top for a simplified (I1) and a full RNA model. The I1 method allowed for a good representation of the mean loading of the tower top for a 360° direction range, for constant and turbulent wind. It is also important to note this method can be quite portable and implemented in most of the tools available in the marked for simulation of floating wind turbines.

TABLE 4: RATIO BETWEEN I1 METHOD AND FULL TURBINE REPRESENTATION FOR THE CASES IN TABLE 1. MEAN OF ALL SEEDS FOR EACH DLC, AND MAX VALUE OBSERVED ON ALL RUNS.

	I1/full model ratio - Mean of 6-seed maxima			
	dlc #1	dlc #2	dlc #3	Max (all runs)
Fairlead tension 1	101%	103%	103%	102%
Fairlead tension 2	102%	102%	103%	100%
Fairlead tension 3	103%	101%	102%	101%
Fairlead tension 4	94%	98%	96%	82%
Fairlead tension 5	106%	100%	102%	107%
Nacelle horizontal acceleration	99%	100%	100%	95%
Offset	101%	100%	101%	101%
Tower bottom overturning moment	98%	98%	99%	97%
Tower top F_X	99%	100%	98%	96%
Tower top F_Y	64%	66%	60%	40%
Platform inclination	101%	101%	102%	104%

TABLE 5: RATIO BETWEEN I1 METHOD AND FULL TURBINE REPRESENTATION FOR STANDARD DEVIATION OF THE TOWER BOTTOM OVERTURNING MOMENT.

	dlc #1	dlc #2	dlc #3
Standard Deviation (I1) [kN.m]	39687.6	39066.9	39325.2
I1/full model ratio - Mean of 6-seed maxima	98%	98%	99%

The method suitability for floating wind turbine design was then investigated. Relevant loads for platform and mooring design were compared between a full and simplified representation. The tower bottom loads, and mooring line ultimate loading estimated from the simplified model and the full turbine model only presented deviations up to <4%. This was observed for a subset of cases that represented extreme conditions for an Atlantic site off the French coast (typically an IEC DLC 6.1). This simplified method for initial studies on platform and mooring lines can be deemed as acceptable.

Expected disagreements on the some of the tower top variables were found but this model is to be used exclusively for the initial stages of platform and mooring design. The mooring line 4 has a difference in the peak tension of 18%. However, it should be noted these DLCs are not driving for these lines (maximal tensions are quite low). The study could perhaps be extended to include the driving load cases of all the components of relevance. One other aspect to be expanded on this study is that the present I1 results are for a rigid tower model and it should be extended to include a model with a flexible tower.

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