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Dynamic response assessment of an offshore wind turbine under Peruvian environmental conditions

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Abstract. This paper presents a dynamic response analysis of an offshore monopile wind turbine to be deployed at a near-shore area in the south-centre part of the Peruvian coast (Marcona). It is a 5 MW three bladed wind turbine that operates in an aggressive offshore environment described by its stochastic behaviour. Thus it is necessary to use a statistical approach for its characterization. The operating wind turbine is simulated using an aero-hydro-servo-elastic computational tool (FAST) that allows the simulation of coupled systems. After the simulation, this work analyses relevant dynamic responses (thrust, torque, shear forces, and bending moments). Time series of these responses at critical zones of the wind turbine are presented. The results indicate high variability of the responses and critical fluctuations located at the mudline. It is found that this variability is due to the additional dynamic loads coming from the ocean waves. This is a big issue to consider when designing a monopile offshore wind turbine operating under the Peruvian environmental conditions.

1. Introduction

During the last decades, there has been a growing interest in the world to make an energy transition to renewable sources. This need has been particularly accelerated in European countries, given the events of recent months related to armed conflicts involving one of the significant fossil energy suppliers [1].

Among the different emerging technologies, wind energy is one of the most developed, apart from solar energy. Evidence of this is that 837.5 GW of wind energy is installed worldwide [2]. Many of the operating wind farms are installed on land. However, there is a significant growth in the development of offshore wind farms as the wind resource at sea is vast and has low variability. In this field, the three leading countries are China, the UK, and Germany, which account for 83 % of the current offshore installed capacity (57.2 GW).

Peru is following the global trend towards renewable energies. In 2008, a legislative decree was published [3]. The purpose of this edict was to promote investment in electricity generation based on renewable energies, aiming to improve the population's quality of life and protect the environment. Several years have passed since the publication of that edict, and at present, several renewable energy power plants are in operation, and several other projects are under development.

Concerning wind energy development in Peru, there are seven wind farms, four in different areas of the northern region (146.8 MW), and three in the southern coastal area (Marcona), with a total installed capacity of 261.45 MW [4]. The unitary power installed in these projects varies between 1.8

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and 3.15 MW. Additionally, there are projects to build wind farms based on turbines of 5.9 MW [5]. This evidences that the Peruvian wind industry is breaking new technological frontiers. It is reasonable to expect that the next frontier to be crossed will be the development of offshore wind farms, given the level of maturity that the Peruvian wind industry is acquiring and the significant advantages that these kind of projects offer in terms of energy production with low intermittency and limited variability.

The current open literature does not provide evidence of any first attempt to employ computational simulation techniques, which considers integrated stochastic approaches, for the design of Peruvian wind energy farms. This type of analysis is crucial for predicting the response of wind turbines for structural health monitoring, oriented to minimize the risk of catastrophic failure since these techniques offer more realistic results in contrast with those obtained using deterministic calculations.

Thus, the present work aims to estimate the dynamic response of a 5 MW three bladed offshore monopile wind turbine (OWT) working under the Peruvian offshore environmental conditions. It is oriented to determine the critical zones and responses from wind and waves that could bring issues during its design process.

2. Peruvian environmental data: wind and wave resource

Public data on wind and wave characteristics of Peru are scarce, and accurate information on environmental variables is crucial for reliable calculations. For this work, estimated and representative values of wind and waves in the Peruvian offshore region have been considered. The geographical area considered for the analysis is the near-shore coastal area of Marcona (Nazca, Peru). This area has been chosen since currently three onshore wind farms are already installed in this zone, so it has a strategic advantage for transmitting the power produced by an eventual offshore wind farm.

The Peruvian wind energy atlas is the first information source to estimate a representative wind speed [6]. This document provides estimated parameters of the Weibull probability distribution that characterizes the wind speed. Based on the atlas charts for a height of 100 m in the Marcona area, the scale factor is approximately 11 m/s, and the shape factor is approximately 5. In this context, the wind speed with a cumulative distribution frequency of 50 % is considered representative for the analysis, i.e., a wind speed (U_W) equal to 10.22 m/s.

The estimation of wave parameters is more complicated since the information is even scarcer than in the case of wind. After an extensive literature review, no historical records on wave parameters could be found. The closest document to providing such data is the work done by [7]. They analysed data collected at a one-hour interval between January 2007 and December 2012. Based on that study and its figure on page 36, an average wave height (H_S) value of 1.75 m and an energy period (T_E) of 10.5 s, which is considered as a first approximation of the peak period (T_P) to be used by the computational simulator, were taken as the representative wave conditions for the area of interest.

These values are considered representative of the environmental conditions of the zone of interest. However, it is necessary to emphasize that the environmental conditions are not deterministic in an integrated analysis. When the numerical wind and wave fields are generated, they become a series of random values related to the wind turbulence and wave spectrums, moving around mean values. These random values can be adequately represented as time series and histograms. In the last case, it can be observed how the values of the generated random sequences are distributed. See Figure 1 for wind speed and Figure 2 for wave elevation. The mean value (μ) and the standard deviation (σ) for each variable are provided in the caption of the figures.

3. Numerical model

A properly integrated simulation of an OWT involves the consideration of all sources of loading that this structure could typically experience. Up to at least nine load sources can be recognized [8], which can be grouped into four main types: Aerodynamic loads originated from wind action on the structure. Hydrodynamic loads generated by the impact of the waves over the structure. Loads related to structural dynamics (mainly inertial loads and their fluctuations, i.e., vibrations). Finally, loads caused by the actuation of the control system. Therefore, an aero-hydro-elastic-servo simulation is necessary to be carried out.

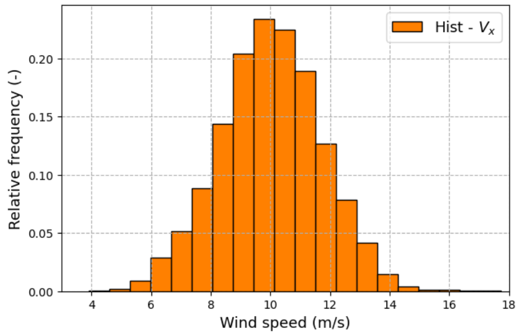

Figure 1. Histogram of wind speed values obtained after discretization of the turbulence spectrum, μ = 10 m/s and σ = 1.70 m/s.

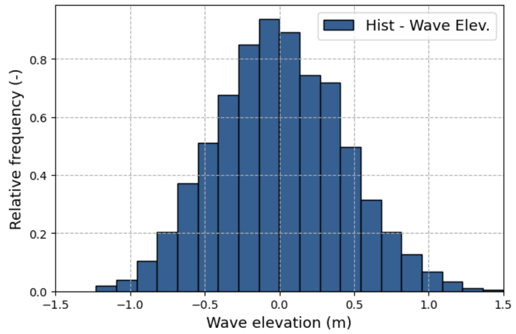

Figure 2. Histogram of wave elevation values obtained after discretization of the wave spectrum, μ = 0 m and σ = 0.43 m.

There are not many specialized computational programs that can consider all these aspects. However, the most widely used in the scientific literature is the FAST program (Fatigue, Aerodynamics, Structures, and Turbulence) developed by the NREL (National Renewable Energy Laboratory) [9], [10]. This program simulates OWTs under conditions very close to real operations. It is also capable of considering the stochastic behaviour of environmental conditions. The results obtained by this program can be considered reliable since it has undergone a series of validation processes [11].

For the present analysis, the model of a 5 MW three bladed OWT is used [12]. The wind turbine is controlled by variable rotor speed and collective pitch. It has a rated wind speed equal to 11.4 m/s. The rotor hub is located at 90 m above the mean sea level. In Figure 3, the wind turbine and tower (grey body) is supported by a monopile (black body) and the sea has a water depth of 20 m.

To set up the simulation it is necessary to make additional considerations related to the stochastic environment, i.e., wind and waves parameters, Figure 4. For the wind simulation and generation of turbulent wind inflow profiles, the TurbSim package also from NREL is used [14]. In this case, the Kaimal turbulence spectral model is considered together with the coherence model given by [15]. The turbulence type is set to Normal Turbulence Model (NTM), and the level of characteristic turbulence is assumed type B. The power-law scheme is used to extrapolate the wind speed at different heights.

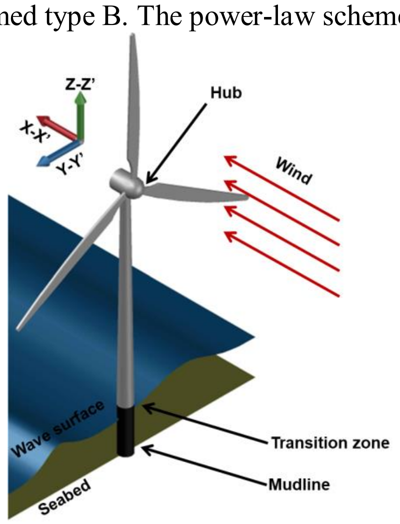

Figure 3. General diagram of the wind turbine, wind speed direction, and coordinate system considered for this analysis [13].

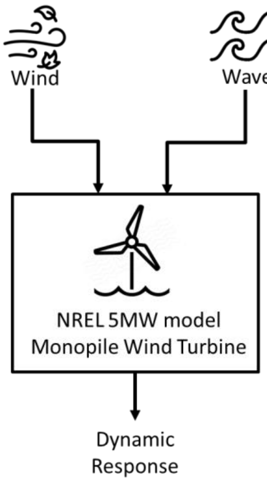

Figure 4. Schematic representation of the process followed to obtain the dynamic responses of the coupled system.

Regarding the configuration for the wave simulation, besides setting H_S and T_P, it is also necessary to define the type of wave spectrum as required by the FAST program. In our case, the "Joint North Sea Wave Project Spectral Wave Model" (JONSWAP) spectrum is chosen as this is the first analysis of the Peruvian marine conditions. In more advanced stages, it will be necessary to determine a specific wave spectrum for the Peruvian sea. FAST performs calculations based on this information to generate the wave profile used in the integrated simulation.

4. Analysis and results

The FAST program is capable of calculating different types of dynamic responses (forces, moments, displacements, and angular deflections, among others). Due to space restrictions, only the most representative dynamic loads will be analysed in this work.

Figure 5 presents the time series of the rotor thrust and torque. It is noted the stochastic nature of these loads. Similarly, Figure 6 shows the time series of the bending moments at the blade root (BRBM). The out-of-plane BRBM, the moment that bends the rotor blades outside their rotation plane, also has a stochastic behaviour. The in-plane BRBM presents an almost cyclic shape as it follows the turbine rotation. The lowest values of bending moments were calculated for the pitching BRBM, which has an irregular fluctuating shape. This moment is associated with the longitudinal axis of the blade, which is characterized by a reduced arm.

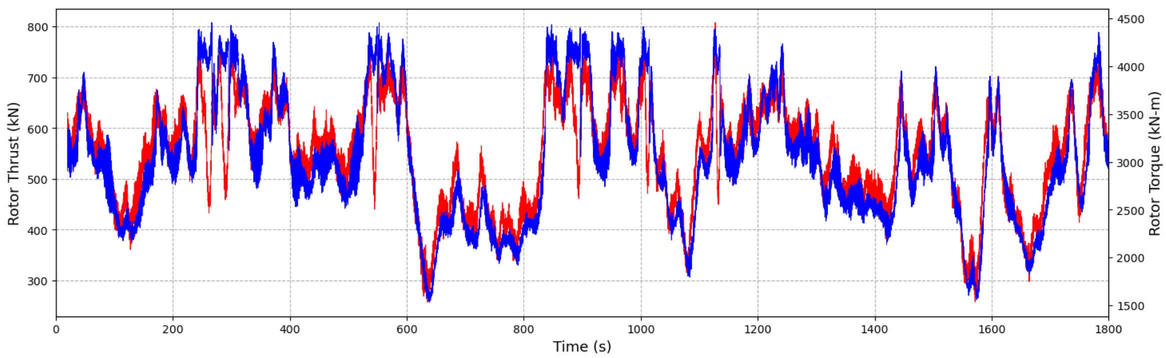

Figure 5. Time series of the rotor thrust (red) and torque (blue).

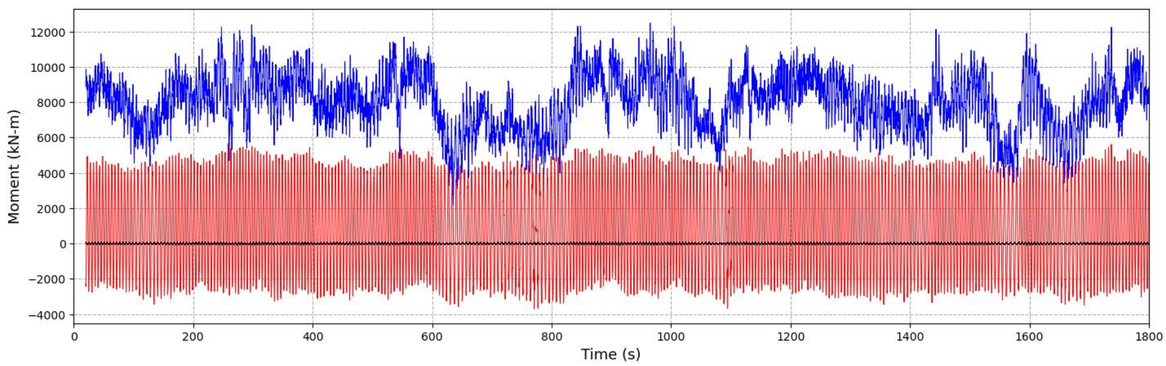

Figure 6. Time series of the BRBM: in-plane (red), out-of-plane (blue) and pitching (black).

The fore-aft shear force (FASF) and the fore-aft bending moment (FABM) are related to the X-X' axis direction, Figure 3. These dynamic responses are evaluated at the mudline (ML) zone, where the monopile joins the seabed, and the tower top (TT), which is the base of the nacelle or hub. Figure 7 shows the behaviour of the FASF at ML and TT over time. From this figure, it can be seen that both responses fluctuate around similar mean values. However, the FASF at ML shows a higher variability.

This behaviour can be attributed to the additional effect of waves since the FASF at TT is mainly influenced by wind, while the FASF at ML considers the combined effect of wind and waves. It means that wave loading does not significantly increase the mean value of the dynamic response but produces more prominent peaks and troughs. It is essential when an extreme value analysis in advanced stages is performed.

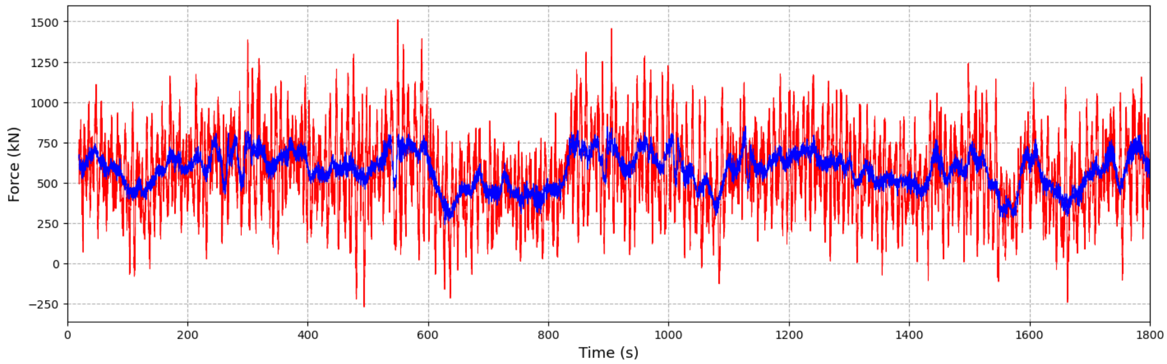

Figure 7. Time series of the FASF at ML (red) and the FASF at TT (blue).

In the case of the bending moments, a significant difference is observed in Figure 8. In this case, the FABM at TT oscillates around a low value compared to the FABM at ML. Here it is important to note that in the case of the FABM at TT, it mainly responds to the effect of wind loads on the rotor and has a small overturning arm (rotor radius). On the other hand, the FABM at ML has a wind and wave contribution. The influence of the wind on the FABM at ML is increased by the very long arm (tower length plus monopile length), whereas the influence of the waves is limited by the water depth.

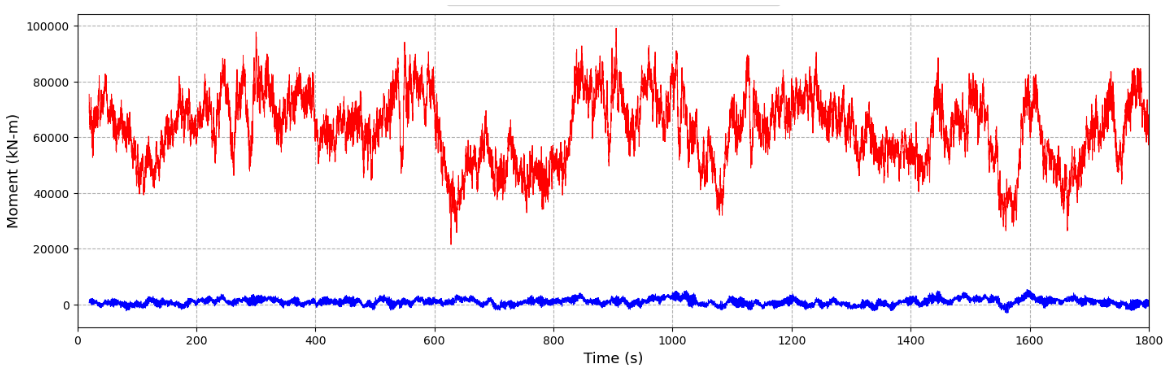

Figure 8. Time series of the FABM at ML (red) and the FABM at TT (blue).

From the previous figures, it is noted that the time series of rotor thrust, torque, out-plane BRBM, FASF at ML, FASF at TT, FABM at ML, and FABM at TT have similar curve profiles, it is due to the action of the turbine control system which keeps the turbine working at maximum power. Table 1 shows the time series' mean, standard deviation, and percentage standard deviation. It can be seen that the dynamic loads have a considerable fluctuation as their percentage standard deviation are around 20 %, with the highest one (FASF at ML) around the 40% due to the additional action of the wave loads. These values are critical when designing this sort of OWT for the geographic study area. The table does not present values for the in-plane BRBM due to their cycle behaviour nor for the pitching BRBM and FABM at TT due to their low mean values.

Table 1. Dynamic load responses calculated in the simulation.

Load	Location	μ	σ	% σ/μ
Thrust (kN)	-	549.77	100.73	18.3
Torque (kN-m)	-	3036.27	652.13	21.5
BRBM (kN-m)	Out-plane	8010.38	1560.59	19.5
FASF (kN)	TT	576.32	107.66	18.7
FASF (kN)	ML	564.18	239.12	42.4
FABM (kN-m)	ML	62785.07	12106.10	19.3

5. Conclusions

In this work, a 5 MW three bladed monopile OWT subjected to the environmental conditions of a near-shore area in the south-centre part of Peru was analysed using an aero-hydro-servo-elastic simulator (FAST). The dynamic load analysis of the wind turbine showed high variability of the dynamic loads. Moreover, the highest variability was calculated to be the fore-alt shear force located at the mudline. It indicates that the additional dynamic loads from the waves are a crucial variable to consider when designing a monopile OWT under the environmental conditions of that Peruvian region.

A similar analysis, but under the scene of a wind farm, will be carried out in future work. It will allow knowing if the environmental conditions of the Peruvian region and the distribution of the OWTs will affect the dynamic load responses.

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