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Effect of wind and wave properties in modal parameter estimates of an idling offshore wind turbine from long-term monitoring data

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\begin{abstract}
In the long-term, the modal properties of Offshore Wind Turbines (OWTs) exhibit significant variations due to constant changes in environmental and operational conditions. These variations have a substantial effect on the wind turbine loads and will lead, for instance, to large uncertainty in fatigue and useful life predictions. Due to the numerous sources of uncertainty, it is difficult to judge how independent environmental or operational parameters influence the modal properties of OWTs. In this work, we make a systematic analysis of the modal parameter estimates extracted from a long-term monitoring campaign in an OWT from the DanTysk wind farm while in its idling condition. We cluster the dataset of vibration responses of the idling OWT into bins of wind and wave characteristics, in order to isolate the effect of the different sources of uncertainty affecting the OWT modal properties. Once the trends in the data are confirmed, we use a simple linear regression model to extrapolate the damping estimates for zero wind speed and wave excitation, thus providing an estimate of the mean and standard errors of the OWT structural damping in the first fore-aft and side-to-side tower bending modes.
\end{abstract}

1. Introduction

Loads in \emph{Offshore Wind Turbines} (OWTs) are highly dependent on the actual damping ratio at each one of the active vibration modes. While structural damping may be considered constant, there are other dynamic effects contributing to the total vibration damping which are dependent on the current environmental and operational conditions. Hence, damping in OWTs is made up of several contributions, including time-dependent contributions from aeroelastic and hydroelastic sources. As these depend on the constantly changing environmental conditions, damping in the general sense is subject to a significant amount of variability and is time-dependent. In consequence, the loads experienced by OWTs are highly non-stationary and uncertain. This is the main reason why fatigue and fatigue-life calculations tend to be accompanied by large uncertainty intervals. One way to reduce the uncertainty in damping estimates and fatigue calculations is to consider the effect of environmental and operational variability.

The best source of information about the actual damping in an OWT corresponds to measurements from the actual structure. Due to the physical size and variable operating conditions of OWTS, and the fact that it is impractical to excite the structure artificially, classical experimental modal analysis techniques are not suitable for accurate modal parameter identifications. Instead, \emph{Operational Modal Analysis} (OMA) is preferred, as it only relies on measured response signals \cite{1,2,3}.

Modal parameter estimates derived from OMA are accompanied by non-negligible estimation uncertainty. In the short-term, uncertainty originates from the underlying randomness of the excitation sources, but also from the settings and limitations of the
Modal Parameter Extraction (MPE) algorithm. In the long-term, variations stemming from environmental conditions and changing operational regimes (standstill, idling, or producing power) also take place.

Short-term uncertainties can be controlled to a certain extent with an adequate adjustment of the parameters of the MPE method and careful selection of the analysis period. In practice, it is necessary to shrink the analysis period to limit the effect of long-term variations (non-stationarity) in the MPE method, while preserving enough data to limit the variance of the estimates. It is also possible to calculate standard errors of modal parameter estimates from short-term variations. This can be done by means of perturbation methods attempting at determining the sensitivity of modal parameters to variations in vibration response data [4–6]. Likewise, Bayesian methods have been introduced as a means to obtain a probability density function of modal parameter estimates conditioned on the observed data [7,8].

When considering long-term monitoring campaigns, the overall variability of modal parameter estimates explodes. This is an issue of particular relevance in the case of OWTs. Main factors comprise [9,10]:

- The significant variability of environmental conditions, which introduces slowly-changing non-stationary dynamics. For instance wind and wave properties, precipitations, soil conditions and temperature.
- The associated changes in operational regimes (standstill, idling, normal power production, and so on) following wind conditions and operational demands, which shift the OWT dynamics between different regimes.

In parallel with that, there is also the problem of tracking and matching the modal parameter estimates obtained at different short-term analysis periods. Due to the considered data volumes, this task needs to be automated in some way. Such procedures are referred to as Automatic Operational Modal Analysis (AOMA) and involve various types of analyses to extract physical poles from the stabilization diagrams and match estimates at different periods. The first task in AOMA involves the extraction of physical poles from stabilization diagrams, which comprises different statistical methods to separate numerical (spurious) modes from the physical ones [11,12]. Available methods can be grouped into clustering techniques [2,3,9,11,12], triangulation [13], or histogram bin analysis [14,15].

These techniques require various adjustments to set their overall performance, including those of the MPE method itself. Often, the required adjustments are made considering a particular structure of the vibration data (number of modes, mode spacing, and so on). However, the signal conditions can easily change due to the non-stationary nature of the vibration response of OWTs [15–17]. Therefore, a single set of adjustment parameters that may be optimal for a single dataset, may be sub-optimal for the entire set of vibration data from the long-term monitoring campaign. This will result in additional uncertainty of the modal parameter estimates and unpredictable sensitivity of mode detection.

Different studies have been directed towards the improvement of the robustness of the automated extraction of modal parameters. These consider extensive validation and adjustment of the algorithm’s parameters [18–20] or post-processing of probable modes [21] based on multiple data sets. Other strategies consider the temporal tracking of probable physical modes identified at different data sets through iterative/recursive algorithms [22,23]. Recent approaches have also focused on the total automation of the physical mode extraction process, leaving the minimum number of decisions to the user [24,25].

Once modal parameters from different intervals are estimated and grouped, it is possible to study their long-term behavior. To this end, modal parameters can be visualized as time-series, and then, with the help of accompanying metadata, different types of dynamic behaviors can be matched with events or operational regimes [26,27]. Furthermore, it is possible to directly correlate modal parameters to measurements of environmental or operational parameters, for instance measured properties of wind or wave excitations [10,26–29]. The latter can be done quite effectively with the use of regression methods, which can do the correlation analysis automatically. Nonetheless, these regressions are highly affected by the uncertainty in the modal parameter estimates and the number of environmental/operational variables that may potentially affect those estimates [10]. As a result, when several factors may affect the dynamics of a structure, there is a non-negligible degree of ambiguity whether an estimated effect actually corresponds to an underlying characteristic of the data or if it is wrongly assumed from the available data.

In this sense, the main aim of this work is to assess—from a model-free perspective—the influence of environmental and operational conditions on the natural frequency and damping estimates of an OWT in the idling condition. More precisely, we are concerned about the effects of wind and wave load characteristics on the modal parameters of an idling OWT. Towards this end, we use long-term field measurements from a 3.6 MW offshore wind turbine (OWT) located at the DanTysk wind farm during the period between June 2019 and June 2021. We use an AOMA method to track the natural frequencies and damping ratios of first fore-aft and lateral tower bending modes in the idling condition, based on the Multiple-reference Ibrahim Time Domain (MITD) modal parameter extraction method. In a parallel study [30], we optimize the parameters of the AOMA method to minimize the estimation uncertainty of modal parameter estimates, and in this work, we use these values to control the estimation uncertainty on a broader range of operational conditions. Then, upon consideration of the complex interactions between wind and wave, we separate the data into different bins of wave periods and significant wave heights, and in each one of them, we examine the influence of wind speed on the natural frequency and damping ratio estimates.

Consequently, the main contribution of this work comprises the systematic analysis of the influence of wind and wave characteristics on the natural frequency and damping ratio estimates of the first four fore-aft and side-to-side tower bending modes of an idling OWT. Such analysis is made at first without imposing a particular model on the data which may bias the trends extracted from the data. Subsequently, we use a linear model to extrapolate the damping value estimates at zero wind speed along with standard errors, which may be interpreted as the isolated structural damping contribution for each one of the first four tower bending modes. The latter may be interpreted as well as a secondary contribution of this work.
This work is organized as follows: in Section 2 we explain the experimental setup and main data sources used in this work; in Section 3 we discuss the main methodological procedures used for data analysis, including data preprocessing and automated operational modal analysis; in Section 4 we initially present segregation of idle cases into a number of clusters containing different levels of wave heights and wave periods. Based on the modal parameters extracted from each cluster of idle cases, we provide the uncertainty bounds for damping estimates for different ranges of wind speeds. Following this, we discuss our findings and compare them with other works in the literature in Section 5, while the final conclusions of this work are presented in Section 6.

2. Experimental setup

The field measurements investigated in this paper originate from a 3.6 MW Siemens offshore wind turbine (DT19) located at the DanTysk wind farm in the North Sea. The rotor diameter reaches 120 m and the tip height reaches 148 m. DT19 is located in the northwestern part of the wind farm and is installed at a water depth of 20.8 m measured from the Lowest Astronomical Tide (LAT) level. The experimental setup and measurement system are the same as presented in [30]. A total of 9 high-accuracy triaxial DC accelerometers (Sensor 1 to 9, model: TRV-3301-1) are installed within the monopile, transition piece and tower structure as shown in Fig. 1. The height of all sensors is defined in relation to the LAT. The accelerometers have a ±1% accuracy within DC-100 Hz. All the sensors are wired to a central data acquisition system, which collects the data and stores it in a local computer that can be remotely accessed. The vibration records are automatically collected in 10-minute intervals during the complete 24-hour period of a day, through the entire monitoring period.

In addition to the acceleration measurements, operational and environmental data are also available from the Siemens Turbine Condition Monitoring (TCM) system installed at the nacelle of the same wind turbine, and from the Research platform in the North and Baltic Sea No. 3 (FINO3). Table 1 lists the operational and environmental data available from the two measurement systems.

![Image of accelerometer locations inside DT19](image_url)

**Fig. 1.** The nine accelerometer locations inside DT19, measured from the seabed. LAT is the lowest astronomical tide level, TP is the transition piece, MP is the monopile, and RNA is the rotor nacelle assembly [30].
Table 1
Main properties of the three data sources used in this work.

<table>
<thead>
<tr>
<th>Data source</th>
<th>Data streams</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated tower monitoring system</td>
<td>Horizontal accelerations at 9 levels in the tower</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Siemens TCM system</td>
<td>Rotor speed, yaw angle, pitch blade angle and wind speed</td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td>Nacelle acceleration (fore-aft and side-to-side)</td>
<td>10 Hz</td>
</tr>
<tr>
<td>FINO3 meteorological mast</td>
<td>Wave period and direction</td>
<td>1/1800 Hz</td>
</tr>
<tr>
<td></td>
<td>Wind direction</td>
<td>1/600 Hz</td>
</tr>
<tr>
<td></td>
<td>Wave height</td>
<td>1/60 Hz</td>
</tr>
</tbody>
</table>

Fig. 2. Frequency distribution of mean wind speeds as a function of mean yaw angles and mean wind directions, separately, shown as wind roses.

2.1. Site conditions

The soil profile applied in the design specifications of DT19 is characterized in the geotechnical report as sand ranging from depths of 0–45 m with varying layers of fine, medium and coarse sand, partly silty and gravelly with occasional thin layers of silt.

Fig. 2 displays the distribution of yaw angles/wind directions and wind speeds observed on site in the form of wind roses. Fig. 2(a) displays the yaw angle and mean wind speed obtained from the TCM system for 70 770 10-minute data blocks (~ 491 days of data). Fig. 2(b) displays the mean wind direction and wind speed from the FINO3 platform measurements on 70 770 10-minute data blocks. The most frequent yaw angle is at 230° (southwest) whereas the most frequent wind direction is directly west (270°) - The second most frequent wind direction is however at 240 degrees. The orientation of the nine accelerometers installed within the tower ranges from 230 to 240 degrees which means that the measured acceleration signals are aligned with the wind and yaw for a large portion of all data collected.

3. Methodology

A description of the overall workflow considered here as well as the related work considered in our parallel publication [30] is depicted in Fig. 3. The workflow starts with a data pre-processing procedure, which involves checking the signal condition through basic statistical checks, plus signal detrending. In parallel, the timestamps of the considered data streams are synchronized, and subsequently, the raw tower vibration data are transformed into coordinates aligned with the yaw angle of the nacelle. With this procedure finalized, we construct a database of joint vibration, environmental and operational data. For subsequent analyses, we select a subset of cases corresponding to the idling condition of the wind turbine. We presently focus on the idling condition to limit the uncertainty in the estimated modal parameters and refrain from the time-periodic effects of an operating OWT. This is the basis for the analyses performed in this work and in our parallel publication [30].
The bottom left of the diagram summarizes the workflow presented in our parallel publication [30], where our main aim is to set up the AOMA method to minimize the uncertainty of damping estimates. To that end, a subset of idling cases of the OWT is selected, considering a confined interval of environmental and operational conditions in an attempt to minimize the effect of ambient variability in damping estimates. Based on that, a study on the adjustment parameters of the AOMA method is carried out, aiming at obtaining the most consistent damping estimates. Complementary to that analysis, the workflow of the present work, shown on the bottom-right side of Fig. 3, aims at assessing the influence of environmental conditions on the estimated damping of the same OWT in the idling condition. The methodology comprises the grouping of idle cases into different clusters according to the significant wave height and wave period measurements. We perform the AOMA procedure, using the optimized adjustment parameters found in [30], and then we proceed to assess the influence of wave height and wind speed on damping and natural frequency estimates. Finally, uncertainty bounds are extrapolated based on the correlation found and the least possible damping estimates are assessed.

The initial part of the data analysis procedure is very similar to that performed in the parallel publication [30]. For completeness, we repeat the description below, with some minor modifications.

3.1. Preprocessing of experimental data

Compensation for nacelle orientation. Fore-aft and the side-to-side motions can be directly identified from the modal parameter estimation after having transformed the local sensor frame of reference into the nacelle coordinate system. To this end, it is necessary
to know the precise orientation of the Rotor Nacelle Assembly (RNA) with respect to each sensor location. The transformation into the nacelle coordinate system is achieved via the linear transformation:

\[
\begin{bmatrix}
    z_{f,a}(nT_s) \\
    z_{s,s}(nT_s)
\end{bmatrix} = \begin{bmatrix}
    \cos \Psi & \sin \Psi \\
    -\sin \Psi & \cos \Psi
\end{bmatrix} \begin{bmatrix}
    z_{X,b}(nT_s) \\
    z_{Y,b}(nT_s)
\end{bmatrix}
\]

(1)

where \(z_{X,b}(nT_s)\) and \(z_{Y,b}(nT_s)\) indicate the original time series in the X and Y directions measured at time \(nT_s\), and \(z_{f,a}(nT_s)\) and \(z_{s,s}(nT_s)\) indicate the transformed fore-aft and side-to-side time series based on the calculated RNA orientation \(\Psi\). This angle is calculated once synchronization is set in place, as explained below.

Data stream synchronization. Since the measured tower acceleration signals and the yaw angle originate from independent measurement systems, it is necessary to synchronize the two data streams. We use the cross-correlation between the tower acceleration data and the nacelle acceleration data obtained from the TCM system for this purpose. Cross-correlation is measured in terms of the Time Response Assurance Criterion (TRAC) calculated between the two vectors formed by the acceleration time series of each of the analyzed signals [31], as follows:

\[
\text{TRAC}_{xy} = \frac{|[x]^T(y)|}{|[x]^T[x]|^{1/2}||y||^{1/2}}
\]

(2)

where \(\{x\} = \{x(T_s) x(2T_s) \ldots x(N \cdot T_s)\}^T\) indicates the column vector with the time series entries recorded in the period \([1, N] \cdot T_s\), and likewise for \(\{y\}\).

Once synchronization is in place, the RNA orientation \(\Psi\) can be derived from the yaw angle plus a small offset in the orientation of individual sensors. This offset can be calculated again by comparison between the highest tower accelerometer (Sensor 1) and the nacelle acceleration signal. Thus, we calculate the TRAC between these two signals while looking for the rotation that maximizes the obtained TRAC. The corresponding angle of rotation for this transformation is subtracted from the yaw angle to find the misalignment between Sensor 1 and the TCM accelerometer. This misalignment was found to be 0.6 degrees and the sensor orientations are adjusted accordingly prior to the transformation of coordinate systems.

Detrending and other statistical checks. The original time-domain signals are detrended upon application of a high-pass Butterworth filter (filter order: 6, cutoff frequency: 0.1 Hz). The filter is designed so that most of the influence of wave and sensor drift is reduced, while the first tower bending modes, near 3 Hz, are kept unaffected. Subsequently, as a final preprocessing step before further analysis, we check the kurtosis, skewness, and RMS values of the signals and remove datasets with marked deviations from the nominal behavior. To this end, we assess the distribution of the kurtosis, skewness and RMS throughout the entire monitoring period and flag the values that significantly deviate from the main distribution. Following this procedure, we are able to detect a small number of outliers that are removed from subsequent analyses. In the end, we obtain that the mean kurtosis of the surviving idle cases is \(3.36 \pm 0.35\) units and the skewness is \(0.16 \pm 0.09\) units, which do not markedly deviate from the reference values of 3 for kurtosis and 0 for skewness of a Gaussian random variable.

3.2. Definition of idle case clusters

Further analysis is based only on data from idling cases to limit the uncertainty from various operational regimes of the OWT. Presently, the idling condition is defined as the operational condition when the offshore wind turbine produces no power (very low rotor speed) but is not at standstill (rotor is locked) and the blades are feathered (blades of the turbine are pitched parallel to the airflow). The latter makes the aerodynamic damping contribution from the rotating blades almost negligible (for increasing rotor speeds, the aerodynamic damping contribution overshadows the remaining damping contributors including hydrodynamic damping, structural damping, soil damping, and the built-in slosh damper). The standstill condition is separated from the idling condition as these possess different dynamic characteristics. Standstill comprises a locked rotor and occurs only during maintenance under mild environmental conditions whereas idling cases are mostly related to scenarios where the turbines are supposed to not produce any energy but the rotor is still free to rotate. In the latter, the variation of environmental conditions is much larger in comparison to standstill. For this reason, idle cases are often more important to investigate from a design point of view. The logical criteria defining the idle condition are summarized in Table 2.

In addition to the idle case criteria, the maximum yaw misalignment to the wind is set to 15 degrees. As the wind direction used to calculate the yaw misalignment originates from the FINO3 database, the calculated misalignment is not a measure of the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Definition of the idle condition ([30]).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cond. 1</td>
<td>Minimum pitch angle (\geq 80) degrees*</td>
</tr>
<tr>
<td>Cond. 2</td>
<td>Maximum rotor speed (\leq 1.5) RPM</td>
</tr>
<tr>
<td>Cond. 3</td>
<td>Minimum rotor speed (\geq 0.005) RPM</td>
</tr>
<tr>
<td>Cond. 4</td>
<td>Maximum variation in yaw angle (\leq 15) degrees</td>
</tr>
</tbody>
</table>

*Rotor blades are feathered in an 82.5-degree pitch angle.
actual yaw error of the wind turbine. The wind direction measured at the turbine itself was not available and there will be a small variation compared to the wind directions measured at FINO3. Because of the discrepancies between the wind direction measured at FINO3 and the true wind direction at DT19, the upper yaw misalignment threshold criterion is set to 15 degrees. For any yaw misalignment below 15 degrees, we expect the wind to be aligned with the yaw direction.

Significant wave heights, $H_s$, are clustered in ranges of 1.28 m for four overlapping mean wave periods, $T_w$, in ranges of 2.82 s. The ranges of wave heights and wave periods for each cluster are listed in Table 3.

### 3.3. Automated operational modal analysis—obtaining stable damping estimates

In this section, we describe an *Automated Operational Modal Analysis* (AOMA) algorithm based on the procedure initially presented in [14]. The AOMA algorithm is based on estimates of the poles and the respective mode shape vectors (or modal participation factor) obtained using any MPE method. Presently, we use the MITD identification method, described in more detail in [15]. This method is closely related to the *Covariance-driven Stochastic Subspace Identification* (SSI-COV) algorithm, and has been demonstrated to produce the lowest estimation uncertainty among several MPE methods [1,32–34].

Our AOMA procedure is split into two parts, the first one aiming at obtaining probable physical modes from a single 1-hour record, the second one aiming at assigning the probable physical modes to some reference poles identified in a previous analysis.

#### 3.3.1. Identification of probable physical poles from 1-hour records

The analysis discussed here is applied on single 1-hour acceleration records, each comprising 9 bi-axial sensors transformed to the fore-aft and side-to-side directions. The MITD method is used for modal parameter extraction operating on PSD-based estimates of auto and cross-correlation functions. The number of correlation lags (lines) and model orders are adjusted to minimize the error of natural frequency and damping ratio estimates, as thoroughly explained in [30]. Once modal parameter estimates are ready, the following procedure is performed to reduce the total set of pole estimates in the frequency stabilization diagram into a smaller subset of probable physical modes:

1. **Calculate histogram of natural frequencies:** A statistical representation of the pole estimates for different model orders on a single 1-hour interval is obtained by calculating the histogram of the natural frequency estimates. Here, the frequency range of interest and the bin width (or the number of bins $N_{bins}$) are provided as adjustment parameters.

2. **Analysis of histogram bins:** For each bin $j = 1, 3, …, N_{bins}$:
   
   (a) **Calculate the number of poles in the bin:** Evaluate the total number of complex conjugate poles on bin $j$ and all the neighboring bins within 5% of the bin’s central frequency. Continue to the procedure below if the total number exceeds a given threshold. Otherwise, move to the next bin.

   (b) **Calculate the MAC matrix in the elements of the selected bins:** The *Modal Assurance Criterion* (MAC) matrix is calculated among all the mode shape vectors on the selected bins. The MAC is defined as follows [35,36]:

   
   $$
   MAC_{rs} = \frac{\left| \langle \Psi_j^H \Psi_s \rangle \right|^2}{\left( \langle \Psi_j^H \Psi_j \rangle \right) \left( \langle \Psi_s^H \Psi_s \rangle \right)}
   $$

   where $\langle \Psi_j \rangle$ and $\langle \Psi_s \rangle$ represent the mode shapes under study, and $^H$ denotes the Hermitian matrix (conjugate transpose) of the mode shape vector.

   (c) **Select a master mode on the current bin:** The master mode is selected as the one corresponding to the column of the MAC matrix with most entries having MAC larger than the threshold $MAC_1$. In case of a tie, the first of these entries would be selected.

   (d) **Construct the set of probable physical modes:** The set of probable physical modes is constructed by assigning the poles in the selected bins to the master mode if their MAC value is higher than a threshold $MAC_2$. The obtained set of modes is then removed, so that these are disregarded in subsequent bin analyses.

---

Table 3

<table>
<thead>
<tr>
<th>Cluster no.</th>
<th>Ranges of wave heights and wave periods</th>
<th>One-hour cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 1</td>
<td>$H_s$ between 0.23 and 1.51 m. $T_w$ between 2.69 and 5.51 s.</td>
<td>2050</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>$H_s$ between 1.51 and 2.79 m. $T_w$ between 4.10 and 6.92 s</td>
<td>677</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>$H_s$ between 2.79 and 4.07 m. $T_w$ between 5.51 and 8.32 s</td>
<td>244</td>
</tr>
<tr>
<td>Cluster 4</td>
<td>$H_s$ between 4.07 and 5.35 m. $T_w$ between 6.92 and 9.73 s</td>
<td>48</td>
</tr>
</tbody>
</table>

$H_s$: Significant wave height; $T_w$: Mean wave period.
Table 4
Input for automated modal parameter extraction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency</td>
<td>$f_s$</td>
</tr>
<tr>
<td>Measurement duration</td>
<td>$T$</td>
</tr>
<tr>
<td>References</td>
<td>Sensor 1 to 9</td>
</tr>
<tr>
<td>MPE method</td>
<td>Multiple-reference Ibrahim Time Domain (MITD)</td>
</tr>
<tr>
<td>Correlation estimator</td>
<td>PSD-based estimation of auto/cross-correlation functions.</td>
</tr>
<tr>
<td>Number of lines (correlation lags)</td>
<td>$N_{\text{corr}}$</td>
</tr>
<tr>
<td>Range of model orders</td>
<td>$M_{\text{est}}$</td>
</tr>
<tr>
<td>Frequency range</td>
<td></td>
</tr>
<tr>
<td>Bin width</td>
<td></td>
</tr>
<tr>
<td>Occurrence threshold</td>
<td></td>
</tr>
<tr>
<td>First MAC threshold</td>
<td>$\text{MAC}_1$</td>
</tr>
<tr>
<td>Second MAC threshold</td>
<td>$\text{MAC}_2$</td>
</tr>
<tr>
<td>Third MAC threshold</td>
<td>$\text{MAC}_3$</td>
</tr>
</tbody>
</table>

3. Calculate summary statistics of probable physical modes: Mean and standard deviations of the pole and mode shape vector estimates are calculated for each set of probable physical modes.

The physical mode extraction procedure described above comprises several adjustment parameters that have to be set by the user. These comprise the frequency range, the bin width (or number of bins), the occurrence threshold (minimum number of pole estimates in a bin), and the \( \text{MAC}_1 \) and \( \text{MAC}_2 \) thresholds. To reduce the number of adjustment parameters the latter MAC thresholds could be defined as equal. Nonetheless, we recommend using two thresholds, so that a more stringent MAC threshold is used to detect the master mode, while a more relaxed threshold can be used to assign modes to the set of probable physical modes, reducing the risk of dropping modes that are still similar enough to the master mode. In the physical mode extraction procedure we opt for analyzing all the bins within 5% of the frequency of the center of the bin, instead of analyzing a specific number of bins. This selection is made to adjust the spread of the analyzed frequency interval as the frequency value increases. Thus, it is possible to examine higher frequency modes in a larger frequency interval, while preserving a small interval to split low frequency modes.

A thorough study on the adjustment parameters of the AOMA was carried out with the aim of obtaining the most consistent damping estimates for a confined interval of idle cases in our parallel publication [30]. These adjustment parameters are applied in the subsequent AOMA, and are all summarized in Table 4. The estimated mode shapes from the MITD method come with an arbitrary scaled phase – the imaginary part of the mode shape vector. In our AOMA procedure, mode shapes are normalized by dividing by the entry with the largest absolute value. This is equivalent to rotating the mode shape in the complex plane, so that the imaginary part is as close as possible to the real axis. The normalization does not influence the modal parameters but seems to slightly affect the MAC calculation between mode shapes obtained from different data sets (on 3rd decimal place).

3.3.2. Identification of reference fore-aft and side-to-side modes

A set of reference mode shape vectors is established for the first four fore-aft and side-to-side tower bending modes. These reference modes are obtained by comparing the probable physical mode shapes identified from 3019 1-hour idle cases (all four clusters) to analytical mode shapes. The analytical mode shapes are derived from a Finite Element (FE) model built on the same geometry and soil conditions of the OWT under study. In the end, we select a single experimental mode shape for each of the modes that have the highest resemblance to those predicted by the FE model and that is identified with the largest number of estimates (a total of 101 available estimates in the model order range of 100 to 200). Details of the reference mode shapes and a comparison with FE model-based ones are provided in Appendix A.

3.3.3. Assignment of modes across data sets

The fore-aft and side-to-side modes are initially identified by comparing the probable physical poles from 1-hour analyses and the reference mode shapes. To this end, a MAC matrix is calculated again, this time between all the master modes of the corresponding set of probable physical modes and the reference mode shapes. The probable physical mode is assigned to a reference mode shape if the MAC value exceeds a third threshold \( \text{MAC}_3 \). Otherwise, the probable physical mode is dropped and analysis is continued until all the sets of probable physical modes are analyzed. This procedure is repeated along all the data sets from the idling condition of the OWT. In the implementation, we have set \( \text{MAC}_3 = 0.8 \) to cope with the variation in the azimuth orientation of mode shapes obtained from different time records. For instance, in the first tower bending modes, there were deviations over 20 degrees in the orientation of the mode shape. Translating this into a MAC value, the value slightly exceeds 0.8.

4. Results

4.1. Clustering data from idle condition

This section describes the results of clustering the vibration data into confined intervals of environmental and operational conditions, more specifically based on wind speed, significant wave height and mean wave period. The aim is to separate the
different potential sources of variation so that their individual influence is studied separately. The clustering process starts with the segregation of cases from the idle state, as explained in Section 3.2. Subsequently, the vibration datasets from the idle condition are split into four clusters of wave heights and periods, as defined in Table 3. The intervals are defined by observing the minimum and maximum significant wave height and wave periods from the OWT in the idling condition, and splitting these ranges into four intervals. Finally, the modal parameters from each vibration dataset are organized into evenly spaced segments of wind speeds.

Fig. 4 shows the mean significant wave heights and wave periods obtained from FINO3. The different colors correspond to the mean wind speeds obtained from the TCM system, as shown in the color bar on the right of the plot. The red dashed boxes indicate the ranges of significant wave heights and periods for each of the four clusters listed in Table 3. In Fig. 4(a), all the available monitoring data (including idling, standstill and in-operation cases) is displayed. This results in 70,770 measured 10-minute data blocks, equivalent to a measurement period of more than 491 days. Fig. 4(b) shows the idle cases that are extracted using the criteria defined in Section 3.2 on the 70,770 measured 10-minute data blocks. This results in a total of 4,753 10-minute idle cases (33 days of data). Red dashed boxes indicate the wave height/period intervals defined in Table 3. While there is no overlapping on significant wave height, we allow some overlapping in the mean wave period to avoid losing data points from the analysis.

4.2. Study of modal parameter estimates obtained with AOMA

Effect of model order in the stability of modal parameter estimates. Modal parameters are estimated using the AOMA presented in Section 3.3 using the settings listed in Table 4. We investigate first the influence of changing model orders on frequency and damping estimates for some selected one-hour idle cases that share similar operational and environmental conditions. These conditions are:

- **Fore-aft mode**: Wind speed confined to the range 6.6 to 7.7 m/s, significant wave height in the range of 0.50 to 1.50 m, and wave period between 3.82 and 4.94 s, resulting in 65 one-hour data sets.
- **Side-to-side mode**: Wind speed in the range of 7.4 to 8.7 m/s, significant wave height in the range 0.50 to 1.50 m, and wave period between 3.82 and 4.94 s, resulting in 107 one-hour data sets.

Fig. 5 shows the distribution of natural frequency and damping ratio estimates for the first fore-aft and side-to-side modes as a function of model order based on the subset of cases explained above. Each graph displays the median value (red squares), 90% confidence intervals (blue patches), and range–min–max– intervals (gray patches) for increasing model orders.

The fore-aft mode stabilizes in terms of damping ratio for model orders greater than 86. In terms of frequency, the fore-aft mode begins to stabilize for model orders greater than 62. The damping ratios for the side-to-side mode are most stable for model orders near 80 and larger. The frequency estimates for the side-to-side mode appear to be most stable for model orders above 112 but the
minimum frequency value is quite stable for model orders above 70. Based on these findings, only model orders ranging from 100 to 200 are considered in the subsequent modal parameter estimation.

Analysis of modal parameters in the clusters. Fig. 6 displays the natural frequencies and damping ratios for the first four tower bending modes in the fore-aft and the side-to-side motion arranged according to the clusters defined in Table 3. The size of the ellipses making up the plot indicates the standard deviations of the natural frequency and damping ratio estimates derived from individual stabilization diagrams. The results indicate a dependency of the position of the cluster centroid, which evidences the dependency of the modal parameters on the sea conditions. There is also evident a notorious variation of the modal parameter estimates within each one of the clusters, which may be attributed to the effect of wind speed, as shall be demonstrated in posterior analysis. Most marked variations are observed in the second fore-aft and side-to-side tower bending modes. In addition, we can observe appreciable variations in the precision in which the modal parameter estimates are obtained at individual 1-hour intervals. Individual estimates of the first fore-aft and side-to-side tower bending modes tend to have lower spread, while higher order modes tend to have a larger variation of the damping ratio estimates. For the first fore-aft and side-to-side tower bending modes, in the modal parameter estimates from cluster 1, some outliers were identified and removed from the analysis. These outliers were characterized by damping ratios exceeding 8%, large standard deviation and overall far from the cluster center (a total of 11 estimates combined for the two identified modes).

Analysis of modal parameter estimates as a function of wind speed. Table 5 provides a detailed statistical analysis of the distribution of the modal parameter estimates (natural frequencies and damping ratios) jointly obtained in clusters 1 to 4, as a function of wind speed. Descriptive statistics comprise median (50-th percentile) and 90% confidence intervals (comprised by the 5-th to 95-th percentiles). In addition, in red color are indicated the extrapolated natural frequency and damping ratios at zero wind speed, based on a linear model of the trends observed on the remaining wind speed intervals. The latter may be interpreted as empirical estimates of the structural damping of the OWT (after removing the effect of wind and wave damping contributions). Hence, for a wind speed of 0 m/s, the 5% and 95% percentiles of the damping ratio are extrapolated to 0.99% and 2.08%, respectively for the fore-aft mode. For the side-to-side mode with 0 m/s wind speeds, these percentiles are extrapolated to 1.24% and 2.58%, respectively.

This analysis is extended to the remaining higher order mode shapes in Figs. 7 and 8. More precisely, Figs. 7 and 8 display the damping ratio estimates as a function of wind speed and significant wave height, respectively, for the first four tower bending
modes in the fore-aft and side-to-side motions. The width and height of the colored ellipses indicate the standard deviation of the damping ratio and natural frequency estimates on individual 1-hour data sets, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In overall, we may evidence the sensitivity of some of the modes to wind and wave properties. In the fore-aft direction, the damping of the second up to the fourth mode seems to be affected by the wind/wave characteristics. In the side-to-side motion, it can be observed evidence of similar effects in the first, second and fourth order modes. Based on the obtained results, and due to the low detection rate, there is no evidence to assess this behavior in the third side-to-side mode.

To complement the previous analysis, in Table 6 we summarize the Pearson correlation coefficients, $r$, calculated between the damping ratio/natural frequency estimates, and the wind speed/significant wave height. In addition, the $\alpha = 0.05$ critical values of the Pearson correlation index are included in the table for reference. The correlation values for the damping ratio confirm the
observations made above and the trends seen in Figs. 7–8 and Table 5. In the modes with a sufficient success rate (over 60%), it can be observed a negative correlation between the natural frequencies and wind speed and significant wave height. Similarly, a positive correlation between the damping ratio and the same wind and wave properties can be observed. In none of the cases, the correlation values drop below the critical value, which means that there is a non-negligible effect of the wind speed and significant wave height in the values of the modal parameter estimates. Nonetheless, in the case of the 1st fore-aft and 3rd side-to-side tower bending modes, the correlation values are quite close to zero.

A more detailed analysis of the effect of wind speed and significant wave height on the damping ratio estimates is provided in Appendix B.
5. Discussion

Correlation between modal parameters and environmental factors. The correlation between damping ratios and loads shows a significant correlation for the side-to-side mode of 0.73 for wind speeds and 0.53 for wave heights as listed in Table 6. The increase in damping ratios as a function of increased loads most likely originates from aerodynamic damping caused by the feathered blades of the rotors and wave loading acting upon the structure from different directions. As explained in [37], the aerodynamic forces are present for the side-to-side mode during idle conditions. The feathered blades create a larger surface in the transverse direction of the nacelle orientation (side-to-side) that interacts with the surrounding air.

In [2], it was shown that higher drag forces in case of higher wind speeds result in higher damping estimates for both the fore-aft and the side-to-side mode. [33] also presented the correlation for the first natural frequency of an OWT (side-to-side) between damping ratios and loads including wind speeds and wave heights of 0.62 and 0.41, respectively. In this paper, the positive correlation between damping and load is expected to be a result of an increased damping contribution from soil non-linearity or hydrodynamics.
Critical value indicates the correlation value for which correlation between the studied variables can be disregarded with 95% of confidence.

Wave heights for the fore-aft mode (0.09 and 0.07, Table 6 and Figs. 7–8). The aerodynamic damping contribution is expected to be negligible in the fore-aft direction and a positive correlation is most likely caused by an increase in damping contribution from soil non-linearity, hydrodynamics or the built-in slosh damper. In the side-to-side direction, the correlation of damping ratio estimates increases to 0.64 in relation to the wind speed, and to 0.44 in relation to the significant wave height. The strength of these correlations seems to be increased in higher order modes, which is especially evident in the 2nd and 4th order bending modes.

Only a small positive correlation is present between the damping ratios and wind speeds and between damping ratios and wave heights for the fore-aft mode (0.09 and 0.07, Table 6 and Figs. 7–8). The aerodynamic damping contribution is expected to be negligible in the fore-aft direction and a positive correlation is most likely caused by an increase in damping contribution from soil non-linearity, hydrodynamics or the built-in slosh damper. In the side-to-side direction, the correlation of damping ratio estimates increases to 0.64 in relation to the wind speed, and to 0.44 in relation to the significant wave height. The strength of these correlations seems to be increased in higher order modes, which is especially evident in the 2nd and 4th order bending modes.

For the natural frequency estimates, there is a negative correlation between natural frequencies and loads (Figs. 7 and 8) that changes on scale of the load. This effect is negligible in lower order modes but starts to be noticeable in higher order modes. The correlation of natural frequency seems to be driven mainly by the significant wave height. A strong correlation is also observed in the two 2nd order bending modes and in the 3rd order bending mode in the fore-aft motion.

Vortex induced vibrations. The RMS value of the side-to-side acceleration was also investigated for all four clusters of idle cases to see if vortex induced vibrations were present. The investigation did not show any significant increase in RMS value for any of the idle cases when compared to the general trend of RMS values calculated on all available data (more than 491 days of acceleration measurements).

Selection of model orders. Only model orders ranging from 100 to 200 were selected for the final modal parameter estimation because the frequency and damping estimates at lower model orders showed significant variations. In [41], the covariance of modal parameters was computed for experimental data obtained from a bridge test at model orders ranging from 1 to 160. The paper reported that the first mode stabilized in terms of frequency after reaching a model order of 53. It is also mentioned that a low standard deviation of a mode in terms of frequency does not necessarily indicate good estimation quality. The mode can also be biased due to a wrong selection of model orders.

Table 5
Median and 90% confidence intervals of the modal parameter estimates of the first fore-aft and side-to-side tower bending modes, split in uniform wind speed ranges from the idling condition of the OWT. Red colored text refers to extrapolated values at zero wind speed.

| Quantity | Percentile 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---------|--------------|---|---|---|---|---|---|---|---|---|---|
| Wind speed (m/s) | – | 0 | [0.72–2.80] | [2.80–4.87] | [4.87–6.95] | [6.95–9.02] | [9.02–11.10] | [11.10–13.17] | [13.17–15.25] | [15.25–17.32] | [17.32–19.40] |
| 1st FA | 0.09 | 1.02 | 1.05 | 1.09 | 1.12 | 1.15 | 1.19 | 1.22 | 1.26 | 1.29 | 1.55 |
| 50% | 1.43 | 1.44 | 1.45 | 1.46 | 1.47 | 1.48 | 1.49 | 1.50 | 1.51 | 1.52 | 1.53 |
| 95% | 2.08 | 2.06 | 2.03 | 1.99 | 1.96 | 1.93 | 1.90 | 1.87 | 1.84 | 1.81 | 1.83 |
| 1st SS | 0.24 | 1.38 | 1.54 | 1.69 | 1.85 | 2.01 | 2.17 | 2.33 | 2.48 | 2.64 | 2.69 |
| 50% | 1.69 | 1.82 | 1.97 | 2.13 | 2.28 | 2.44 | 2.59 | 2.75 | 2.90 | 3.06 | 3.09 |
| 95% | 2.58 | 2.66 | 2.77 | 2.87 | 2.97 | 3.07 | 3.16 | 3.28 | 3.38 | 3.48 | 3.51 |
| 1st FA | 0.314 | 0.314 | 0.313 | 0.313 | 0.313 | 0.313 | 0.312 | 0.312 | 0.312 | 0.312 | 0.312 |
| 50% | 0.315 | 0.315 | 0.315 | 0.315 | 0.314 | 0.314 | 0.314 | 0.313 | 0.313 | 0.313 | 0.313 |
| 95% | 0.318 | 0.318 | 0.317 | 0.317 | 0.316 | 0.316 | 0.315 | 0.315 | 0.314 | 0.314 | 0.314 |
| 1st SS | 0.317 | 0.317 | 0.316 | 0.316 | 0.316 | 0.316 | 0.315 | 0.315 | 0.315 | 0.315 | 0.315 |
| 50% | 0.319 | 0.319 | 0.318 | 0.318 | 0.318 | 0.317 | 0.317 | 0.317 | 0.317 | 0.317 | 0.317 |
| 95% | 0.322 | 0.322 | 0.321 | 0.321 | 0.320 | 0.320 | 0.319 | 0.319 | 0.318 | 0.318 | 0.318 |

Table 6
Pearson correlation values calculated between natural frequency/damping ratio estimates with the mean wind speed and significant wave height the first four tower modes in the fore-aft and side-to-side motion. The success rate is based on 2019 one-hour idle cases.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Pearson correlation</th>
<th>FA</th>
<th>SS</th>
<th>FA</th>
<th>SS</th>
<th>FA</th>
<th>SS</th>
<th>FA</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st FA</td>
<td>( \dot{f}_{n, U} )</td>
<td>–0.53</td>
<td>–0.31</td>
<td>–0.68</td>
<td>–0.66</td>
<td>–0.64</td>
<td>0.21</td>
<td>–0.29</td>
<td>0.33</td>
</tr>
<tr>
<td>1st SS</td>
<td>( \dot{\zeta}, h_s )</td>
<td>–0.64</td>
<td>–0.55</td>
<td>–0.91</td>
<td>–0.90</td>
<td>–0.48</td>
<td>0.25</td>
<td>–0.08</td>
<td>0.27</td>
</tr>
<tr>
<td>2nd FA</td>
<td>( \dot{f}_{n, U} )</td>
<td>0.09</td>
<td>0.62</td>
<td>0.60</td>
<td>0.50</td>
<td>0.47</td>
<td>0.03</td>
<td>0.83</td>
<td>0.34</td>
</tr>
<tr>
<td>2nd SS</td>
<td>( \dot{\zeta}, h_s )</td>
<td>0.07</td>
<td>0.44</td>
<td>0.83</td>
<td>0.77</td>
<td>0.57</td>
<td>0.19</td>
<td>0.67</td>
<td>0.26</td>
</tr>
<tr>
<td>Success rate [%]</td>
<td>99.1</td>
<td>87.6</td>
<td>78.6</td>
<td>68.3</td>
<td>84.6</td>
<td>3.9</td>
<td>85.8</td>
<td>36.1</td>
<td></td>
</tr>
<tr>
<td>Critical value</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td>0.004</td>
<td>0.003</td>
<td>0.015</td>
<td>0.003</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

\( f_n \): Natural frequency; \( \zeta \): Damping ratio; \( U \): mean wind speed; \( h_s \): significant wave height.

Critical value indicates the correlation value for which correlation between the studied variables can be disregarded with 95% of confidence.

Only a small positive correlation is present between the damping ratios and wind speeds and between damping ratios and wave heights for the fore-aft mode (0.09 and 0.07, Table 6 and Figs. 7–8). The aerodynamic damping contribution is expected to be negligible in the fore-aft direction and a positive correlation is most likely caused by an increase in damping contribution from soil non-linearity, hydrodynamics or the built-in slosh damper. In the side-to-side direction, the correlation of damping ratio estimates increases to 0.64 in relation to the wind speed, and to 0.44 in relation to the significant wave height. The strength of these correlations seems to be increased in higher order modes, which is especially evident in the 2nd and 4th order bending modes.

For the natural frequency estimates, there is a negative correlation between natural frequencies and loads (Figs. 7 and 8) that is almost identical in most cases for the wind speeds and wave heights. For the fore-aft mode, the correlation is –0.53 and –0.64 between wind speeds and wave heights, respectively. A similar correlation is found in the natural frequency estimates on the side-to-side mode of –0.55 with wave height, but only –0.31 when related to the wind speed (Table 6). In the latter case, the change in the natural frequency seems to be driven mainly by the significant wave height. A strong correlation is also observed in the two 2nd order bending modes and in the 3rd order bending mode in the fore-aft motion.

Wave misalignment to the wind was not taken into consideration in the definition of clusters of idle cases but the influence on the modal parameters was investigated. The modal parameters and wave misalignment did not have any evident correlation and outliers in terms of either frequency or damping ratio cannot be explained by wave misalignment.

10-minute time average values of the ambient temperature were available in the monitoring data. However, it was not possible to see an effect on the modal parameters originating from the temperature, based on correlation analysis. The effect of soil erosion (scouring) also could not be studied in the present analysis, as the soil depth was not part of the monitoring data. Still, there is a possibility that this factor may influence the modal parameters of the OWT, as has been demonstrated in other works [38–40].
Overall damping from confined intervals of operational and environmental data. The 90% confidence intervals for each wind speed range listed in Table 5 bound the damping ratios of the fore-aft mode within a minimum range of 0.52% (segment 10) and maximum range of 1.04% (segment 2) for the first tower bending mode. In the corresponding side-to-side mode, the 90% confidence intervals bound the damping ratios within a minimum range of 0.84% (segment 10) and 1.28% (segment 2). The ideal damping value applied in the original design of the dedicated tower is 6% logarithmic damping which corresponds to a damping ratio of 0.95%. This is only slightly conservative in comparison to the 5% fractile of the damping ratios extrapolated at 0 m/s wind speeds for the fore-aft at 0.99%. However, the design damping value is significantly lower if compared to the median damping ratio extrapolated at 0 m/s wind speeds for the fore-aft at 1.43%.

In [42], the contribution from soil non-linearity was shown for a simulated model of an offshore wind turbine to increase from 0.2% at low wind speeds up to around 1.3% at wind speeds of 12 m/s for various soil profiles. Based on these findings, the positive correlation between damping and loads may be explained by an increased contribution of soil damping. The decrease in contribution from soil damping followed by wind speeds larger than 12 m/s as shown in [42] is not present in the current data sets. This is probably because of the limited range of wind speeds available or due to a significant contribution from aerodynamics or hydrodynamics.

In [33], the average damping ratio was estimated between 2% and 2.5% for a similar offshore wind turbine across a large span of wind speeds and wave heights. For wind speeds approaching 0 m/s in this paper, the damping ratio was extrapolated to values close to 1.5% and more than 1.8% for the fore-aft and the side-to-side mode, respectively. These values are comparable to the extrapolated median damping ratios reported in the current paper at 0 m/s (1.43% and 1.69%) and also fall within the 90% confidence interval.

In [2], results were synthesized from 14 days of continuous monitoring during mostly idle or parked conditions with wind speeds ranging between 0 and 16 m/s. The mean damping ratio was found to be 1.86% and 2.49% for the fore-aft and the side-to-side mode, respectively. The standard deviation for each of the modes was found to be 0.85% and 0.97%. Both mean values fall within the 90% confidence interval across all wind speeds reported in the current paper but the standard deviations of damping ratios are significantly larger. [2], reports standard deviation of the damping ratio of 0.85% and 0.97% for the fore-aft and the side-to-side damping. The standard deviation of damping ratios across all segments of wind speeds listed in Table 5 is found to be 0.30% and 0.46% for the fore-aft and the side-to-side mode, respectively.

In [3], the mean damping ratios for the fore-aft and side-to-side mode are reported for different ranges of wind speeds with a mass-tuned damper active. The mean damping ratios for the fore-aft mode are in general close to the 95% fractile or slightly larger whereas most of the damping ratios for the side-to-side mode fall within the 90% confidence intervals listed in Table 5. The mean damping ratio of 2.77% that is attached to the highest wind speeds (16–18 m/s) is significantly larger than the 95% fractile reported in the current paper for the fore-aft mode (1.84%). For the side-to-side mode, the damping ratio of 3.19% within the same range of wind speeds is only slightly larger than the median value listed in Table 5 (2.9%). The overall damping ratio for the fore-aft mode is reported to be 1.7% which is 0.4% to 0.5% larger than the reported overall damping ratio obtained where the tuned mass damper was inactive at wind speeds ranging between 4 and 6 m/s. This is a significantly higher overall damping in comparison to the values listed in Table 5 for wind speeds ranging between 4.87 and 6.95 m/s (1.46% median damping ratio). This most likely means that the built-in slosh damper is not contributing to a significant amount of damping in this range of wind speeds. Apart from the damping contribution of aerodynamics and soil non-linearity, a potential contribution from the slosh damper may explain the increase in damping at higher wind speeds.

6. Conclusion

This work has been focused on a systematic analysis of the influence of wind and wave characteristics on the modal properties of an idling OWT. The analysis was performed based on data from a monitoring campaign comprising nine acceleration sensors synchronized wind and wave characteristics. An AOMA procedure was developed to extract and track the modal parameters from vibration responses. Subsequently, we correlated the estimated modal parameters of the OWT with wind and wave properties. Initially, we take a totally model-free approach, in which the data is separated into clusters, which are analyzed independently. On each one of the clusters, we could confirm how wind and wave properties influence the center of mass of the distribution and its dispersion. Subsequently, we perform correlation analysis and linear regression to quantify the trends observed in the data and extrapolate the values at zero wind speed. The latter was interpreted as the values of structural damping. From this procedure, we are able to obtain the least possible uncertainty bounds for the first four fore-aft and side-to-side tower bending modes of the OWT, which could be compared with its design values.

In general, it can be concluded that wind and wave characteristics bear a non-negligible influence on most of the modal parameters of the OWT. Damping ratios tend to have a positive correlation with wind speed and significant wave height. On the contrary, natural frequencies tend to decrease as wind speed/significant wave height decreases. The strong correlation between these variables makes it challenging to quantify from the present analysis which of these variables is driving the change in the dynamics. Nonetheless, it is quite plausible that both environmental factors have an important joint influence on the dynamics of an offshore wind turbine.

Several factors remain to be studied, including soil depth (soil degradation), temperature, turbulence and structural aging/deterioration, among others. Analysis of these and other parameters with a more subtle influence on the dynamics would possibly require much longer monitoring periods and improved modal parameter extraction techniques. Likewise, more thorough statistical analyses are necessary to assess the complex correlations between environmental/operational factors and modal properties. The use of methods that can continuously track the changing dynamics of the OWT could prove advantageous in this sense. Likewise, methods that can extract modal parameters from in-operation (rotating) wind turbines, can also be very helpful in this regard.
CRediT authorship contribution statement

Jonas Gad Kjeld: Writing – original draft, Visualization, Conceptualization, Methodology, Software, Formal analysis, Investigation. Luis David Avendaño-Valencia: Supervision, Writing – review & editing, Conceptualization. Jonas Vestermark: Supervision, Conceptualization, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Experimental reference mode shapes

In this Appendix, we briefly compare the reference mode shapes with mode shapes obtained from a Finite Element (FE) model of the OWT under study. The FE model is designed with the same geometry and soil conditions as the OWT. It comprises the fore-aft (FA) and side-to-side (SS) motions and uses the mass moment of inertia of the Rotor-Nacelle-Assembly (RNA) in the fore-aft direction. The experimental mode shapes are obtained by analyzing the probable physical poles derived from the analysis of 3,019 1-hour idle cases. The MAC matrix of the whole set of poles is calculated, and the most common modes are identified. The identified mode shapes can be observed in the plots in Fig. 9, while the corresponding natural frequencies are summarized in Table 7.

<table>
<thead>
<tr>
<th>Method</th>
<th>1st bending</th>
<th>2nd bending</th>
<th>3rd bending</th>
<th>4th bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE model FA</td>
<td>0.3088</td>
<td>1.1965</td>
<td>2.0061</td>
<td>4.3000</td>
</tr>
<tr>
<td>FE model SS</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Experimental FA</td>
<td>0.3145</td>
<td>1.6682</td>
<td>3.2613</td>
<td>4.6418</td>
</tr>
<tr>
<td>Experimental SS</td>
<td>0.3183</td>
<td>1.6421</td>
<td>3.1499</td>
<td>4.9322</td>
</tr>
<tr>
<td>Difference FA (%)</td>
<td>1.8459</td>
<td>1.6682</td>
<td>1.6682</td>
<td>1.6682</td>
</tr>
<tr>
<td>Difference SS (%)</td>
<td>3.0764</td>
<td>36.4062</td>
<td>36.4062</td>
<td>36.4062</td>
</tr>
</tbody>
</table>

Overall, we observe a difference between the natural frequency and mode shapes in both the experimental and FE model-based estimates. Observing the mode shapes in Fig. 9, it can be concluded that the difference is actually not that significant, with the exception perhaps of the 3rd order bending modes. Still, we can see that the main shape is preserved. Otherwise, the natural frequencies exhibit a larger difference, which is more marked in the second and third bending modes. Nonetheless, such differences may be expected, in part due to the limited accuracy of the FE model but also due to the effect of environmental and operational conditions.

Appendix B. Linear regression of modal parameter estimates on wind/wave properties

In this Appendix, we investigate further the effect of wind and wave properties in the natural frequencies and damping ratio estimates. To this end, we estimate the parameters of the linear model $y = ax + b$, where $x$ is the predictor (mean wind speed or significant wave height), and $y$ is the response variable (natural frequency or damping ratio). In addition, $a, b$ are the linear regression parameters, with $a$ indicating the slope and $b$ indicating the intercept of the function. These parameters are estimated using ordinary least squares based on the data point from each one of the wave period/significant wave height clusters. In Table 8 are reported the mean ($\mu$) and standard deviations ($\sigma$) of the linear regression parameter estimates for the different tower bending modes and for each one of the clusters, and the number of data points (count) used to estimate those parameters. The standard deviations of the regression parameters are calculated as the square root of the diagonal entries of the parameter covariance matrix $(X'X)^{-1}b^2$, where $X$ is the regression matrix and $\delta^2$ is the estimate of the residual variance.
Table 8
Intersection and slope of linear functions fitted to the median damping values and wind speeds ($U$)/significant wave heights ($H_s$) for each cluster. Count refers to the number of one-hour idle cases.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cluster</th>
<th>$U$</th>
<th>$H_s$</th>
<th>Count</th>
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<tr>
<td></td>
<td></td>
<td>Intercept $b$</td>
<td>Slope $a$</td>
<td>Intercept $b$</td>
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Fig. 9. Experimental reference mode shape vectors. Orange lines indicate FE mode shapes and blue lines indicate experimentally obtained mode shapes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
References


