Damping estimation of an offshore wind turbine on a monopile foundation

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Abstract: The work presented in this study describes a comparative study between different techniques aimed at identifying the damping values of an offshore wind turbine on a monopile foundation. It will be shown that damping ratios can directly be obtained from vibrations of the tower under ambient excitation from wave and wind loading. The results will be compared with the damping values obtained from a commonly used overspeed stop. Ambient vibration tests have the strong advantage of being more practical and less demanding for the wind turbine in comparison with the overspeed stop. Several identification algorithms, the standard exponential decay method, alternative procedures in the time domain as well as more advanced operational modal analysis techniques in the frequency domain will be applied to the experimental data. These data have been obtained during a short measurement campaign on an offshore wind turbine in the Belgian North Sea. The results of the used methods for estimating the modal damping of a wind turbine excited by ambient excitation will be discussed and compared. This study also presents some aspects related to the practical implementation of the measurements.

1 Introduction

1.1 Relevance

Many large-scale offshore wind farm projects use monopile foundations to realise a cost effective design. During the design of these monopile structures fatigue because of combined wind and wave loading is one of the most important problems to take into account. Coincidence of structural resonances with wind turbine dynamic forces can lead to large amplitude stresses and subsequent accelerated fatigue. For this reason, the wind turbine rotor blades and support structure are designed to avoid resonance coincidence. In particular, the current practice is to design the wind turbine support structure in such a way that the tower fundamental resonance does not coincide with the fundamental rotational (1P) and blade passing (3P for three-bladed turbines) frequencies of the rotor [1].

In recent studies [2], it was, however, suggested that for the commonly used ‘soft-stiff’ design methodology, designers should not only consider discrete coincidence of 1P and 3P with fundamental support structure resonance but should also acknowledge the fact that the dynamic amplification associated with fundamental resonance has finite bandwidth. Even those systems with 1P and 3P away from resonance can still be excited in the fundamental mode. Experiments performed by the Maritime Research Institute Netherlands (MARIN) and the Energy Research Centre of the Netherlands (ECN) confirmed, by using model tests of breaking waves against an offshore wind turbine model with realistic flexibility, that breaking waves could induce significant oscillations and accelerations in the turbine [3]. This can have significant effect on the lifetime of the wind turbine.

Damping ratios are crucial for lifetime predictions as the amplitude of vibrations at resonance are inversely proportional to these ratios. The overall damping of the first bending mode of an offshore wind turbine consists of a combination of aerodynamic damping, damping because of vortex shedding, damping because of constructive devices, such as a tuned mass damper and additional offshore damping that consists of damping from wave creation because of structural vibration, viscous damping because of hydrodynamic drag, material damping of steel and soil damping because of inner soil friction [1, 4]. A rather high aerodynamic damping is achieved when the turbine is in production state. However, in a non-production state as well as in perpendicular rotor direction, for example, as relevant in case of wind and wave misalignment, no aerodynamic damping is present. In this last case, the overall damping mainly consists of additional damping. Real damping ratios are very difficult to predict by numerical tools and, therefore measurements on existing offshore wind turbines are crucial to verify the existing design assumptions [1]. We, therefore consider it as an important challenge to develop and apply new measurement procedures, complementary to the presently available standards and guidelines, for estimation of damping of offshore wind turbines in various operating and ambient conditions. This will enable validation of the design models and allow for accurate lifetime prediction and online lifetime evaluation.
Identification of modal parameters on a full-scale operating wind turbine is particularly difficult and in the research community a lot of effort still goes into the development of suitable methods to tackle this problem [5]. Classical experimental modal analysis methods cannot be applied because the input force because of wind cannot be measured. For this reason, OMA methods were developed to identify the modal parameters from the response of a mechanical structure in operation to unknown random perturbations [6–8].

In the past few years, the identification of output-only data has received a considerable amount of attention. Adapting model-based system identification techniques (e.g. maximum likelihood (ML) estimator, least-squares complex exponential estimator, subspace techniques) for use with output-only data, has created the possibility of estimating modal models for in-operation structures excited by ambient noise and vibration (e.g. wind and waves etc.) [9–12]. These algorithms require the spectral densities of the outputs as primary data. The output spectra form the basis for frequency-domain output-only modal analysis [8].

These methods work under the assumption that the system is linear time invariant in the analysed time interval and that the excitation is white noise in the frequency band of interest. Only in this situation the output spectra perfectly represent the system. However, because of the presence of rotating components and their corresponding harmonic force contributions or because of the wind wave interaction with the structure, introducing coloured noise contributions, wind turbines can fail to comply with the OMA assumptions. Depending on the operating conditions, some of the non-white noise force contributions may coincide or be close to a natural frequency of the wind turbine, thus masking its contribution because of higher energy and causing the identification process to fail.

In [13], the applicability limits of OMA to operational wind turbines were discussed. It was clearly demonstrated that some important OMA-assumptions regarding the loads acting on the wind turbines are not satisfied for classic OMA techniques. As such the authors demonstrated that for weak and strong wind excitation the spectra of the aerodynamic forces are not flat but are characterised by peaks at rotational frequencies and few lower harmonics. They concluded that one must not expect classic OMA techniques to provide correct results in these frequency regions.

To solve these problems, current OMA methods need to be improved. Although some solutions have already been presented, they can usually only tackle one of the specific problems listed above [14, 15]. Another difficulty is that in many applications such as helicopters or wind turbines the frequencies of the harmonic disturbances can vary in time. In order to deal with time varying harmonic disturbances a new method was proposed in [16] based on parametric modelling of the frequency variation combined with the use of an ML estimator. Recently, a completely new OMA approach, based on transmissibility measurements, was proposed that increases the reliability and applicability of OMA techniques [17]. This innovative new approach does not always require the assumption that the forces are white noise sequences. Therefore this new approach makes it possible in certain cases to apply OMA in the presence of arbitrary operational forces (e.g. coloured noise and impacts). In recent work it was shown that the transmissibility-based OMA approach is able to deal successfully with harmonics when the loads are correlated [18]. The proposed transmissibility-based OMA approach, therefore looks very appealing. However, despite the good results obtained so far there is a need for more basic research in order to continue to refine this approach and correctly position it in relation to other OMA methods.

In [13] also, the violation of the time invariance assumption in the case of operational wind turbines was discussed. During operation a wind turbine is subjected to different motions of the substructures, for example, yaw-motion of the nacelle, individual pitching of the blades and overall rotation of the rotor. Rotor rotation represents a severe problem from the structure invariance point of view [13]. However, if one is interested in the fundamental tower modes the effect of the rotor can be considered as an external excitation [13]. During operation the yaw motion does not present a considerable problem for modal analysis as the yaw speed is very slow and the nacelle does not move constantly. Therefore it is possible to select datasets when the yaw does not change at all. Pitch-controlled wind turbines are designed to operate at variable speed, thus the assumption of linear time invariant system may not be valid. This poses a serious problem in the selection of an adequate length of the time signal for the analysis [6]. Even though the duration should be long enough to allow a proper estimation of modal parameters and in particular of damping values, on the other hand it is necessary to use signals obtained for ‘quasi-stationary’ conditions to comply with the invariant system assumption. Different regimes can be identified, for example, pitch-regulated regime; RPM-regulated regime and parked conditions. Obviously, in parked conditions the system is time invariant and all OMA assumptions are fulfilled. Also, in the RPM-regulated regime OMA is possible as the pitch is set to minimum and does not change a lot in time.

2 Offshore measurements

Within the project two measurement campaigns have been planned. The first short measurement campaign focused on performing an overspeed test with the aim of obtaining a first estimate of the damping value of the fundamental for-aft vibration mode of the wind turbine. During the second long-term measurement campaign we will continuously monitor the vibration levels and the evolution of the frequencies and damping of several fundamental modes of the tower and foundation. Both the resonance frequencies and damping values are crucial to quantify the reliability and the lifetime of offshore wind turbines both in the design phase as during its life cycle. These parameters will also be analysed to see if they can provide indications about the current state of the soil and foundation characteristics, for example, monitoring scour development [19]. The long-term measurement campaign will last between 6 months and 1 year. The measurement campaigns are performed at the Belwind wind farm, which consists of 55 Vestas V90 3 MW wind turbines. The wind farm is located in the North Sea on the Bligh Bank, 46 km off the Belgian coast (Fig. 1).

The hub-height of the wind turbine is on average 72 m above sea level. Each transition piece has a height of 25 m and a weight of 120 ton. The tests are performed on the BBCO1-turbine that is located to the north of the wind farm.
directly next to the offshore high voltage substation. The wind turbine is placed on a monopile foundation structure with a diameter of 5 m and a wall-thickness of 7 cm. The actual water depth at the location of BBCO1 is 22.9 m and the monopile has a penetration depth of 20.6 m. The soil is considered stiff and mainly consists of sand.

The structures instrumented in this campaign are the tower and transition piece. Measurements are taken at four levels on nine locations using a total of ten sensors. The measurement locations are indicated in Fig. 2 by yellow circles. The locations are chosen based on the convenience of sensor mounting, such as the vicinity of platforms. The chosen levels are 67, 37, 23 and 15 m above sea level. The interface level between the transition piece and the wind turbine is at 17 m above sea level. There are two accelerometers mounted at the lower three levels and four at the top level. The chosen configuration is primarily aimed at identification of tower bending modes. The two extra sensors on the top level are placed to capture tower torsion. Accelerometers have been selected, which have a high sensitivity and are able to measure very low frequent signals. This is necessary considering that the modal frequencies of interest, for the wind turbine structure, are expected to be around 0.35 Hz, and the expected vibration magnitude is very low, especially during ambient excitation. During the short measurement campaign, discussed in this paper, the sensors 7 and 8 were not yet installed.

The data-acquisition system is mounted in the transition piece (green circle in Fig. 2). The project invested in a ‘multi-purpose monitoring system’ to support dedicated R&D projects in the field of offshore wind energy. It can be used to monitor several parameters, for example, accelerations and strains, on existing offshore wind turbines. There was the demand for a robust data-acquisition system considering the harsh offshore conditions and any downtime had to be avoided taking into account the high cost related with working offshore. Since the project aims at characterising the dynamics of an operational turbine under various operating conditions, it is also necessary that the data are acquired over a long period of time. This requires the data-acquisition system to be remotely monitored and capable of automatic startup in case of power shutdowns. Bearing in mind the specific demands of the project a Compact Rio system of National Instruments was used (Fig. 3). An important reason for choosing this particular type of system is its high flexibility to measure different types of signals. There is also the possibility to synchronise this Compact Rio system with other Compact Rio systems. This is especially interesting keeping in mind that the long-term measurement campaign might be extended with measurements on the drive train and the blades.
The data-acquisition software allows for continuous monitoring of the accelerations. The data-acquisition system was programmed to acquire data with a sampling ratio of 5 kHz. Considering the frequency band of interest and in order to reduce the amount of data the recorded time series have been filtered with a band-pass filter and re-sampled with a sampling frequency of 12.5 Hz. After the down sampling and filtering a coordinate transformation was performed, because the accelerometers are mounted on the tower. Therefore in order to measure the vibrations along the axis of the nacelle, it is necessary to take the yaw-angle into account by transforming them into the coordinate system of the nacelle [20].

The software measures continuously and sends data every 10 min to the server that is installed onshore using a dedicated fibre that is running over the seabed. All data receives a time-stamp from an NTP timeserver in order to be able to correlate them with the SCADA and Meteo data. The measurements can be monitored in real-time using the online scope-function. Finally, in order to classify the operating conditions of the wind turbine during the measurements of SCADA data (power, rotor speed, pitch angel and nacelle direction) is gathered at a sample rate of 1 Hz. In order to also monitor the varying environmental conditions, the ambient data (wind speed, wind direction, significant wave height and air temperature) is being collected at 10 min intervals.

3 Damping estimation

3.1 Description of the tests

In this paper, the damping of the first for-aft mode of the wind turbine will be estimated by using the data obtained during an overspeed stop and during ambient excitation. Fig. 4 shows an example of measured accelerations during the overspeed test and during ambient excitation.

The objective is to obtain an estimate of additional offshore damping. This is the overall damping excluding aerodynamic damping and damping because of vortex shedding or installed damping devices [21]. Therefore both during the overspeed test and during the ambient excitation test the installed tuned mass damper was turned off. During ambient excitation the wind speed was always very low <4.5 m/s and the pitch angle was around 80.5°. This permits us to assume that aerodynamic damping can be neglected. For the overspeed stop the wind speed was the minimum required at 6.5 m/s. This allows the wind turbine to speed up until 19.8 rpm. This is the speed at which the wind turbine is automatically stopped and the pitch angle is put on 88.2°. Hence, here also we can assume that aerodynamic damping could be neglected a few seconds after the overspeed stop took place. Therefore the measured additional offshore damping will consist of damping from wave creation because of structure vibration, viscous damping because of hydrodynamic drag and material damping of steel and soil damping because of inner soil frictions [21].

3.2 Overspeed stop

The overspeed test is commonly used to accurately identify modal damping ratios. The damping ratios can be obtained by fitting an exponential function to the relative maxima of the decaying time series and extracting the damping ratio from the parameters of the fitted expression. This method
assumes that the decay has only the contribution of a single mode. When this assumption is not met it may result in high scatter and might give wrong estimates for the damping. This is especially the case for closely spaced modes where it might not be possible to obtain a decaying vibration with just the contribution of one mode [22].

During an overspeed stop the wind turbine speeds up until it reaches 19.8 rpm. Then the wind turbine is automatically shut down. During this stop the pitch angle is changed from $-2.5^\circ$ to $88.2^\circ$ in a couple of seconds. The thrust release because of this sudden collective pitch variation excites the tower mainly in the wind direction as can be seen in Fig. 5. Note that on the figure the wind direction is shown from bottom to top.

In the beginning of the decay, the for-aft (FA) mode is dominant, but by the end of the decay both the FA mode and the side-to-side (SS) mode contribute to the movement. This can be observed in Fig. 6.

At a certain moment the phase between the FA and SS responses changes to $180^\circ$ causing the measured vibration to change direction. The figures show that it is definitely interesting to plot the FA movement and SS movement to check if the vibration is dominated by one mode before applying the exponential decay method.

3.2.1 Time domain analysis: From the above conclusion we can assume that the decay in the beginning of the exponential decay is mainly dominated by the FA mode and that performing an exponential decay analysis is expected to give acceptable estimates for damping of the FA mode. In order to have a better fit, extra points by using a spline function have been interpolated between the extremes. The method was applied to the measured accelerations of the highest three levels in the direction of the wind. The data were pre-filtered using three different band-pass filters. The fitting was performed between 0.8 and 0.2 of the maximum acceleration. The results are shown in Figs. 13–15 and in Table 1.

It is expected that the estimates using the narrow band-pass filters $0.3–0.5$ Hz around the frequency of the first FA mode of the wind turbine are likely to be the most correct ones (Fig. 7), as this band is filtering any effects of higher vibration modes of tower and blades. Moreover, as the offshore wind turbine is continuously excited by ambient excitations coming from the wind and waves, we can no longer speak of a free vibration test. Also, this may introduce errors in the damping estimation approaches. During this experiment the wave period was around 0.29 Hz, as will also be discussed in the next section. Only the last band-pass filter excludes this continuous wave excitation.

We can conclude that the above technique is expected to give good damping estimates after applying a proper band-pass filter to isolate the contribution of the mode under analysis. This approach can face difficulties when several modes, for example, first FA and SS mode, are present with close frequencies or when coloured ambient force contributions are present, for example, waves.

3.2.2 Frequency domain analysis: Instead of analysing the data in the time domain, one can also perform the analysis in the frequency domain. The fast Fourier transformation of the decaying functions can directly be used as input for the analysis methods in the frequency domain [23]. Fig. 8 shows the fast Fourier transformation of the accelerations obtained on the three different levels in both the FA and SS direction. One can clearly identify the dominant peak from the first FA mode about 0.35 Hz. We can also identify some smaller peaks with a frequency higher than 1 Hz. These peaks are related to higher tower bending modes and blade modes. We can also clearly observe some peaks below the dominant frequency. These peaks are related to the waves. The significant wave height during the tests was 0.5 m.

The frequency domain identification algorithms [8–10] can now be applied to a matrix with a single column containing the fast Fourier transformation of the free decays measured during the overspeed test. During this analysis we used again the data between 0.8 and 0.2 of the maximum acceleration. An initial estimate of the damping ratios was obtained with a least squares estimator in the frequency domain, using polynomials with orders between 1 and 60 [9]. The fitting was performed in the frequency range 0.1–2 Hz. These results can be used to construct a stabilisation chart from which the user can try to separate the physical poles (corresponding to a mode of the wind turbine) from the mathematical ones. By displaying the

Fig. 6 Movement seen from above (left) and accelerations (right) on three levels in FA and SS direction at the end of the decay of the overspeed stop
poles (on the frequency axis) for an increasing model order (i.e. number of modes in the model), the diagram helps to indicate the physical poles since, in general, they tend to stabilise for an increasing model order, whereas the computational poles scatter around. The construction of the stabilisation chart is nowadays one of the requirements for a modal parameter estimation algorithm, and it has become a common tool in modal analysis. In Fig. 8 the stabilisation diagram is displayed. In the stabilisation diagram algorithm used in this paper we evaluate for every pole, the distance to the nearest pole calculated with the previous model order and we plot:

- a red s, if distance is smaller than 1%,
- a blue f, if only frequency variation is smaller than 1%,
- a purple d, if only damping variation is smaller than 5%,
- a black o, if neither the pole, nor the frequency, nor the damping ratio stabilise

In the stabilisation diagram we can clearly see that the dominant mode about 0.35 Hz is well identified and resulted in a clear stable line. The damping ratio of this mode was found to be 1.05% (Table 2).

The peak below the dominant mode was identified with a much higher damping and has a frequency of 0.29 Hz. This perfectly coincides with the wave period of the waves with a wave direction almost in line with the nacelle. During the overspeed stop the wave period was around 3.4 s. Note that this confirms that waves can induce significant oscillations and accelerations in the turbine as was stated in [3]. The wave frequency is close enough to the resonance frequency of the fundamental mode of the wind turbine to have a dynamic amplification. Therefore waves can have a significant effect on the lifetime of the wind turbine and should definitely be taken into account when performing fatigue calculations.

Note that this approach fits a polynomial function with multiple modes and therefore overcomes the limitations of the traditional procedure of fitting an exponential decaying function to the measured accelerations in the time domain. The frequency domain technique uses a model that starts from the knowledge that the overall vibration consists of different modes. The method easily identifies some of the higher tower bending modes and blade modes as different stable poles. Therefore the results are not affected by the fact that multiple modes are present in the measurements.

<table>
<thead>
<tr>
<th>Band</th>
<th>0.01–1.5 Hz</th>
<th>0.1–0.8 Hz</th>
<th>0.3–0.5 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 1</td>
<td>1.10%</td>
<td>1.12%</td>
<td>1.04%</td>
</tr>
<tr>
<td>level 2</td>
<td>0.98%</td>
<td>1.15%</td>
<td>1.05%</td>
</tr>
<tr>
<td>level 3</td>
<td>0.86%</td>
<td>1.16%</td>
<td>1.05%</td>
</tr>
</tbody>
</table>

Table 1 Estimated damping ratios on three levels using different band-pass filters

Fig. 7 Exponential fitting on FA acceleration on three levels direction after applying a band-pass filter of 0.01–1.5 Hz (left) 0.1–0.8 Hz (middle) 0.3–0.5 Hz (right)

Fig. 8 Fast Fourier transformation of the accelerations obtained on three different levels in both the FA and SS direction (left). Stabilisation diagram after applying the least squares frequency domain estimator (right)
The obtained result therefore corresponds closely with the previous results when we applied a narrow band-pass filter around the FA-mode.

### 3.3 Ambient excitation

Ambient vibration tests have the strong advantage of being very practical and economical, as they use the freely available ambient wind wave excitation. Furthermore, the data are collected during the normal use of the structure and consequently the identified modal parameters are associated with realistic vibration levels. An OMA was performed with the rotor slowly rotating (0.2 rpm). In the 40 min of recorded data (just before the overspeed stop was performed) the wind had an average speed of about 4.5 m/s. The nacelle was put into the direction of the wind. Fig. 9 shows the movement of the tower in the FA and SS direction during two successive time segments.

One can observe that the movement is mainly in the FA direction, that is, the direction of the wind, but there is also a contribution of the SS movement. The tower does not vibrate purely in the wind direction, both the FA mode as the SS mode are present, resulting in an additional movement perpendicular to the wind.

#### 3.3.1 Correlation driven analysis in the time domain:

When using the vibrations measured during the ambient vibrations one can calculate the correlation function of the measured accelerations. It has been shown that the output correlation of a dynamic system excited by white noise is proportional to its impulse response [23]. Therefore it is possible to estimate the modal damping ratio of the modes under analysis from the obtained correlation in a similar way as from the decaying time series obtained during an overspeed stop. By fitting again an exponential function to the relative maxima of the auto-correlation functions the damping ratio can be extracted from the parameters of the fitted expression. Fig. 10 shows the normalised auto-correlation functions of the sensors on the third level in the SS direction and the FA direction together with their exponential fit using 40 min of data.

As mentioned above this approach can only provide good estimates for damping when the decay consists of 1 mode. When this is not the case and there is strong coupling between 2 modes, for example, between the FA and the SS mode, one will not be able to see a nice decay.

The auto-correlation of the FA movement still seems to have a nice decay in the beginning, but some small

![Fig. 9](image-url) Movement seen from above on three levels in FA and SS direction during ambient excitation at two different moments in time

![Fig. 10](image-url) Exponential fitting of an autocorrelation function of the sensors on the third level in the FA direction (left) and SS direction (right)

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*Table 2* Estimated damping of the first FA-mode using overspeed data and OMA in the frequency domain

| Damping ratio FA mode | 1.05% |

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3.3.2 Correlation driven analysis in the frequency domain: In a similar way as with the decaying functions obtained during the overspeed test, the fast Fourier transformation of the positive time lags of the correlation functions can directly be used as input for the analysis methods in the frequency domain. As mentioned in the introduction this is only valid in the case when the ambient forces can be considered as stochastic white noise in the frequency band of interest.

The matrix containing the fast Fourier transformations of the auto- and cross-correlation functions between the accelerations at all measurement points and the accelerations at each chosen reference point can be used as input for the analysis methods in the frequency domain. In this paper, the two sensors on the third level (cf. Fig. 2) in the FA and SS directions were chosen as reference signals. Fig. 11 shows the spectra obtained from the correlation functions, when using 40 min of data and using the first 512 positive time lags. The transformation of the correlation function into spectra is also preceded by the application of an exponential window to reduce leakage and the effect of the noise terms in the tails of the correlation functions. During the estimation process the damping ratios can easily be corrected for this window [22].

After applying the poly-reference least square estimator [12] to the 6 by 2 matrix containing the correlation functions, in the frequency band of 0.1–2 Hz, we can construct the stabilisation diagram as is shown in Fig. 11. Note that this approach fits again a polynomial function with multiple poles and therefore the results are not affected by the fact that multiple modes are present in the measurements as was the case for the previous correlation driven analysis in the time domain. This analysis identifies several modes within the selected frequency band and moreover it results in three stable poles around the dominant peak. The poly-reference least square estimator is able to identify the two closely spaced poles that correspond, respectively, with the first FA mode at 0.358 Hz and with the first SS mode at 0.365 Hz and another stable pole just below the dominant peak that has a frequency of 0.31 Hz. This last one corresponds again with the wave period during the ambient test that was now slightly higher in comparison with the overspeed test. Table 3 gives the estimated damping values for the first FA mode and the first SS mode.

The damping value of the first FA mode corresponds well with the one that was found using the data from the overspeed test (Table 4). In the SS direction we find a slightly higher damping. This might be explained because of the presence of some small aerodynamic damping effects in this direction considering the pitch angle of 80.5° [13]. According to [24], the aerodynamic forces are present even at standstill because of the larger blade surface that interacts with surrounding air when the tower vibrates in the SS direction.

3.3.3 Detailed analysis using correlation driven OMA in the frequency domain: In the above analysis important parameters that could be chosen were the length of the used time segment and the number of time lags taken from the correlation function used for spectra calculation. The spectra resolution, which is controlled by the number of time lags taken from the correlation functions, should be high enough to well characterise all the modes within the selected frequency band. At the same time, it should be kept as low as possible to reduce the effect of the noise.

Therefore in this paragraph, different time segment lengths and different numbers of time lags taken from the correlation functions will be evaluated. This leads to different spectra resolutions. When it comes to the estimation process the selected model order of the polynomials used to perform least squares

Table 3 Estimated damping ratios using the autocorrelations both in FA and SS direction using different band-pass filters

<table>
<thead>
<tr>
<th>Band</th>
<th>0.01–1.5 Hz</th>
<th>0.1–0.8 Hz</th>
<th>0.3–0.5 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 1 FA</td>
<td>0.89%</td>
<td>0.89%</td>
<td>0.84%</td>
</tr>
<tr>
<td>level 1 SS</td>
<td>1.81%</td>
<td>1.79%</td>
<td>1.59%</td>
</tr>
</tbody>
</table>

Table 4 Estimated damping ratios on the levels both in FA and SS direction using different band-pass filters

<table>
<thead>
<tr>
<th>Damping ratio FA mode</th>
<th>Damping ratio SS mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.04%</td>
<td>1.25%</td>
</tr>
</tbody>
</table>
fitting can also significantly affect the identified damping ratios and resonance frequencies.

In order to visually show the effect of these parameters, it is interesting to plot the results of the above stabilisation diagram in an alternative way by using a plot where we show the estimated damping values against the estimated resonance frequencies for different model orders. This has been done in Fig. 12 for the case of 40 min of ambient data using 512 positive time lags of the correlation functions and a model order up to 60.

One can immediately easily identify the two clusters with similar frequencies and damping values, for the first FA mode and the first SS mode. These two clusters correspond

![Image]( Cluster-plot, damping against frequency, of the first FA-mode and first SS-mode for all modal orders, when using 40 min of data and 512 positive time lags and a model order up to 60)

Fig. 12

with the stable lines around the dominant peak in the previously obtained stabilisation diagram of Fig. 11. This plot nicely illustrates that the scatter on the damping is higher than for the resonance frequencies. However, for the main mode of interest about 0.358 Hz, the first FA mode, the scatter on the damping is rather low. Next to the first FA mode we can identify the cluster that corresponds with the first SS mode. Although this mode was less present in the data, the damping values are less well identified and thus more scattered.

Instead of now selecting one stable pole in the stabilisation diagram, corresponding with one model order, to obtain an estimate of the damping, as was done in the previous section, one can perform a statistical analysis on the obtained clusters. This approach yields in a more reliable and robust way the mean and standard deviation of the estimated damped natural frequencies and damping ratios for each cluster. Note that this standard deviation is not a value for the overall expected standard deviation on damping during various measurements, but should only be considered as a kind of quality indicator of the estimation process. One can also choose not to use the first model orders of the estimation process for the clustering algorithm, because the low order estimates are often of less quality and because different system poles only show up as stable lines for higher model orders. Also an outlier analysis could be applied on each cluster before calculating the mean-value and standard deviation. In Fig. 12 the mean values and standard deviations of the damping ratios are plotted on top of the clusters.

We can now continue with our analysis focusing on the effect of the selected time length and time lags on the estimated damping value of the fundamental foundation mode. Fig. 13 shows the results of the algorithm when using 40 min of ambient data for different points taken from the correlation functions, respectively, 256, 512, 1024 and

![Image]( Cluster-plot, damping against frequency, of the poles for all modal orders zoomed around the first FA mode, when using 40 min of data and using, respectively, 256, 512, 1024 and 2048 time lags taken from the correlation functions (top) comparison of results of first FA mode (bottom))

Fig. 13
2048 positive time lags. When we look to the results of the first FA mode (Fig. 13, bottom) we can observe that, when using 256 points and 2048 points, the standard deviations are slightly higher than for the other two cases. Also, for the second cluster for the case of using 256 time lags a high standard deviation is found. When using 1024 points the standard deviation is rather low, however, similar as for the 2048 case, the identified frequency and damping values seem to be a bit overestimated. This can be attributed to the fact that in both these cases the estimation process failed to identify the nearby SS mode. Therefore it tries to fit the data with one pole, whereas in fact there are two modes present in the data-set of 40 min. This inevitably leads to a bias on the results. In the case of 512 time lags the 2

Fig. 14 Cluster-plot, damping against frequency, of the poles for all modal orders zoomed around the first FA mode, when using, respectively, 40, 30, 20 and 10 min of data and 512 time lags taken from the correlation functions (top) comparison of results of first FA mode (bottom)

Fig. 15 Cluster-plot, damping against frequency, of the poles for all modal orders zoomed around the first FA mode, when using four successive data-sets of 10 min and 512 time lags taken from the correlation functions (top) comparison of results of first FA-mode (bottom)
nearby modes were identified and we found mean values for the frequency and damping with acceptable standard deviations. To sum up, this analysis shows that concerning the number of time lags taken from the correlation functions, 512 time lags seem to be adequate.

Fig. 14 shows the results of the algorithm when using 40, 30, 20 and 10 min of ambient data and 512 time lags. We can see that the standard deviation increases with the decrease of the used time length. In the case of the used data-set of 10 min the weakly present SS mode could no longer be identified. This latter must not be considered as a general conclusion, but only means that by using short time segments one might have the risk of not identifying a mode simply because it was only weakly excited during the considered time segment.

We can conclude that if one wants to obtain a high quality estimate of the damping value of the first FA mode a time length of 30 min or more of constant ambient and operating conditions is desired. On the other hand, when using only 10 min of data the standard deviation is higher than for the longer data sets, however, the mean value is still comparable. Therefore 10 min can be considered sufficient to find estimates for the damping of the first foundation modes with a minimum acceptable quality. This is an important conclusion if one wants to use estimates of resonance frequencies and damping values in, for example, continuous structural health monitoring of the offshore wind turbine. A time segment of 10 min allows assuming that the ambient condition, for example, wind speeds stayed more or less constant. Ten minutes is also the commonly used time interval for the SCADA data and the Meteo data, and thus has the advantage of making future analyses of the data easier.

Finally, an analysis was conducted on three more successive data sets of 10 min using 512 time lags of the correlation functions. All data sets resulted in a clearly identifiable cluster for the first FA mode (Fig. 15). Fig. 15 also gives again an overview of the mean values for damping ratios and resonance frequencies and standard deviation on damping ratios for the first FA mode. From these figures we can already see the variations on the estimates one might expect when using successive data-sets with similar ambient and operating conditions. We can note a variation from around 0.8 to 1.2%.

4 Conclusions and future work

The analysis of the measured data showed that the ambient vibration tests together with the application of state-of-the-art output-only identification techniques can provide good estimates of the modal damping ratios of offshore wind turbines. However, care should be taken when analysing such data. High scatter is to be expected when the analysis is not carefully conducted. For the methods in the frequency domain, results can depend, for example, on the measured time, on the number of positive time lags of the correlation functions used and the model order. A detailed discussion on this topic can also be found in other papers [9, 10, 22, 25].

Using the exponential fitting approach one can encounter difficulties when several modes, for example, first FA and SS modes, are present with close frequencies or when coloured ambient force contributions are present, for example, waves. Proper filtering might be required in such cases in order to obtain good estimates of the damping. The techniques presented in the frequency domain estimate the correct damping ratios even when several modes are present in the overall vibration and their natural frequencies are close. Furthermore, the OMA approach also allows extracting the higher modes.

The approach for dealing with ambient data, presented in this paper, preferably requires long time series of constant ambient and operating conditions. However, when one wants to use these techniques for continuous monitoring, one will not always be able to guarantee these long time segments of time invariant conditions. It has been shown that using data-segments of 10 min is still sufficient to find estimates for damping of the first foundation modes with an acceptable quality. A further optimisation of the results might be expected by using the ML estimators and taking the noise information into account [26] or using the new transmissibility-based OMA approach [18].

As future work the data obtained during the long-term monitoring campaign will be analysed. It is therefore the objective to provide in the near future a statistical analysis of the damping ratios and resonance frequencies of the fundamental tower/foundation modes of an offshore wind turbine in function of the operating and ambient conditions. This should help us to obtain a better understanding in the damping-effects in offshore wind turbines and to estimate in a better way the real lifetime of wind turbines.

So far we can conclude that the results obtained in this short term measurement campaign are in good agreement with GL recommendations for additional offshore damping for piled support-structures [4]. Taking into account a possible scatter of the results we can state that the additional offshore damping of the fundamental mode is between 0.8 and 1.2%. It is, however, recommended to perform this type of measurements and analysis on several turbines as the obtained results may depend on different parameters, for example, type of foundation structure and soil conditions.

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6 References

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